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Construction Quality Management for Remedial Action and Remedial Design Waste Containment Systems

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Technical Guidance Document

CONSTRUCTION QUALITY MANAGEMENT FOR REMEDIAL ACTION AND REMEDIAL DESIGN WASTE CONTAINMENT SYSTEMS

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Risk Reduction Engineering Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs, and regulations of the U.S. Environmental Protection Agency; the permitting and other responsibilities of State and local governments; and the needs of both large and small businesses in handling their wastes responsibility and economically.

This document provides design guidance on final cover systems for hazardous waste landfills and surface impoundments. We believe that the final cover, if properly designed and constructed, can provide long-term protection of the unit from moisture infiltration due to precipitation. The cover system presented herein is a multilayer design consisting of a vegetated top layer, drainage layer, and low-permeability layer. Optional layers which may be required for site-specific conditions are also discussed. Rationale is provided for the design parameters to give designers and permit writers background information and an understanding of cover systems.

This document is intended for use by organizations involved in permitting, designing, and constructing hazardous and non-hazardous waste land disposal facilities and in remediating uncontrolled hazardous waste sites.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

This Technical Guidance Document is intended to augment the numerous construction quality control and construction quality assurance (CQC and CQA) documents that are available for materials associated with waste containment systems developed for Superfund site remediation. In general, the manual is oriented to the remediation project manager (RPM) who must administer these projects.

This document reviews the significant physical properties associated with the construction materials used in waste containment designs and reviews the sampling and acceptance strategies required for Construction Quality Management. The first chapter reviews the minimum Federal regulatory requirements for waste containment systems. Key elements of these systems are identified. The second chapter reviews the key physical properties and conformance tests required to verify these properties. The third chapter reviews sampling methods and acceptance criteria that are used to verify key physical properties during construction.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS

List of Figures

List of Tables

SECTION 1.0

Construction Quality Management

The purpose of this document is to define procedures that ensure construction materials and practices used in waste containment installations meet the project specifications and the requirements of related remedial settlement orders. The specific objectives are:

- Define Construction Quality Management (CQM) and the responsibility of the parties involved in the project
- Define and list the waste containment systems described in 40 CFR 240 and 300
- Identify components used to construct the waste containment systems
- Identify the elements that are used to assemble these components and the key properties of these elements that require testing in the field to measure the quality of the construction
- Present sampling methods to obtain unbiased representative samples from these key elements
- Present examples of how to implement these sampling methods on selected elements.

This document is written for the design engineer responsible for preparation of project plans, specifications, and the CQM program, and the EPA remedial project manager (RPM) charged with implementing the CQM program. The document focuses on those factors most susceptible to field construction problems. It is assumed that the materials to be used at each site have been designed (thickness, type, etc.) and evaluated (EPA Method 9090, etc.) by others. These elements are assumed to meet the applicable or relevant and appropriate requirements (ARAR) for the site as determined in the remedial investigation and feasibility studies (RI/FS) process under CERCLA (1).

CQM is defined as the pro-active planning, development and implementation of both Construction Quality Assurance (CQA) and Construction Quality Control (CQC) throughout the project. In order to ensure a functional and safe waste containment system, quality must be present in all phases of the project, including:

- Pre-construction phase
    - conceptual design
    - design
    - preparation of project specifications
    - preparation of CQA/CQC documents

- Construction phase
    - material property testing
    - installation testing

- Post-Construction phase
    - care of installation until it goes into service
    - inspection and maintenance of the facility
    - operations

While CQM must be included in every phase of the project and a system of testing and oversight must be used throughout the project, the focus of this document is CQM during the construction phase of the development of a waste containment system.

1.1 CQA/CQC Objectives

Construction Quality Assurance (CQA) consists of a planned series of observations and tests to ensure that the final product meets project specifications. CQA plans, specifications, observations, and tests are used to provide quantitative criteria with which to accept the final product.

On routine construction projects, CQA is normally the concern of the owner and is obtained using an independent third party testing firm. For the waste containment applications covered by this guide, the CQA program is also commonly a certification tool used by EPA to ensure that the project is properly implemented. The independence of the third party inspection firm is therefore of great importance. This is particularly true when the owner is a corporation or other legal entity that has under its corporate 'umbrella' the capacity to perform the CQA activities. Although these CQA personnel may be registered professional engineers, there may exist a perception of misrepresentation if the activity is not performed by an independent third party.

The CQA officer should fully disclose any activities or relationships with the owner which may impact his impartiality or objectivity. If such activities or relationships exist, the CQA officer should describe actions that have or can be taken to avoid, mitigate, or neutralize the possibility they might affect the CQA officer's objectivity. Regulatory representatives can then evaluate whether these mechanisms are sufficient to ensure an acceptable CQA product.

Construction Quality Control (CQC) is an ongoing process of measuring and controlling the characteristics of the product in order to meet manufacturer's or project specifications. CQC is a production tool that is employed by the manufacturer of materials and contractor installing the materials at the site. CQA, by contrast, is a verification tool employed by the facility owner or regulatory agency to ensure that the materials and installations meet project specifications. CQC is performed independently of the CQA Plan. For example, while a geomembrane liner installer will perform CQC testing of field seams, the CQA program will require independent CQA testing of those same seams by a third party inspector.

The CQA/CQC plans are implemented through inspection activities which include visual observations, field testing and measurements, laboratory testing and the evaluation of the test data. Inspection activities are typically concerned with four separate functions:

> Quality Control (QC) Inspection by the Manufacturer provides an in-process measure of the product quality and its conformance with the project plans and specifications. Typically, the manufacturer will provide CQC test results to certify that the product conforms to project plans and specifications.
>
> Construction Quality Control (CQC) Inspection by the Contractor provides an in-process measure of construction quality and conformance with the project plans and specifications. This allows the contractor to correct the construction process if the quality of the product is not meeting the specifications and plans.
>
> Construction Quality Assurance (CQA) Testing by the Owner (Acceptance Inspection) performed by the owner usually through the third party testing firm, provides a measure of the final product quality and its conformance with project plans and specifications. Due to the size and costs of a typical remedial action/remedial design (RA/RD) project, rejection of the project at completion would be costly to all parties. Consequently, CQA testing takes place throughout the construction process. This allows deficiencies to be found and corrected before they become too large and costly. CQA represents an important tool to EPA to ensure that the remediation is properly implemented.
>
> Regulatory Inspection is often performed by a regulatory agency to ensure that the final product conforms with all applicable codes and regulations. In some cases the regulatory agency will use the CQA documentation and the as-built plans or 'record drawings' to confirm compliance with the regulations.

EPA Report 530-SW-86-031 (NTIS PB87-132825) entitled "Construction Quality Assurance for Hazardous Waste and Land Disposal Facilities" sets forth key items that should be included in the CQA/CQC Plan:

1) **Responsibility and Authority** - The responsibility and authority of the various organizations and personnel involved in permitting, designing, and building the facility should be described.

2) **Personnel Qualifications** - The qualifications of the CQA officers and supporting CQA inspection personnel should be presented.

3) **Inspection Activities** - The observations and tests that will be used to ensure that the construction or installation meets or exceeds all design criteria, plans, and specifications for each component should be described.

4) **Sampling strategies** - The sampling activities, sample size, methods for determining sample locations, frequency of sampling, acceptance and rejection criteria, and methods for ensuring that corrective measures are implemented should be presented.

5) **Documentation** - Reporting procedures for CQA activities should be described in detail in the CQC/CQA plans.

The responsibility and authority of project organizations and personnel (item 1 above) are included in the above EPA Report and will not be discussed here. Guidelines for the qualification of personnel (item 2) are also included in the EPA report, but are being revised and will be presented in an upcoming document. Currently, a program to certify CQA inspectors is administered by the National Institute for Certification of Engineering Technicians (NICET). Inspection activities for specific components of a waste containment system have been presented in a variety of EPA papers and Technical Guidance Documents (TGDs) (2, 3, 4, 5, 6, 7) and will only be summarized in this report.

This guidance document begins with a brief overview of waste containment systems and components along with the key physical properties that require monitoring during construction and installation. A major focus of this document is the sampling strategies and acceptance criteria which are used in the CQA plan (item 4). Suggested CQA documentation requirements are provided in several EPA TGDs detailing waste containment components (8, 9, 10).

1.2 Regulatory Waste Containment Systems and Objectives

Under current RCRA and CERCLA regulations, there are four distinct waste containment systems: surface impoundments, waste piles, landfills, and on-site isolation. Each containment system is built of components with distinct engineering functions, (e.g. moisture barrier, reinforcement, drainage, etc). In turn, each component is composed of elements , i.e., individual materials or products, that have particular field inspection requirements. This chapter provides a brief overview of the four waste containment systems and their major components. Chapter 2 describes the elements and their respective CQA field testing requirements. Chapter 3 reviews common field sampling strategies and acceptance criteria and provide examples of their application.

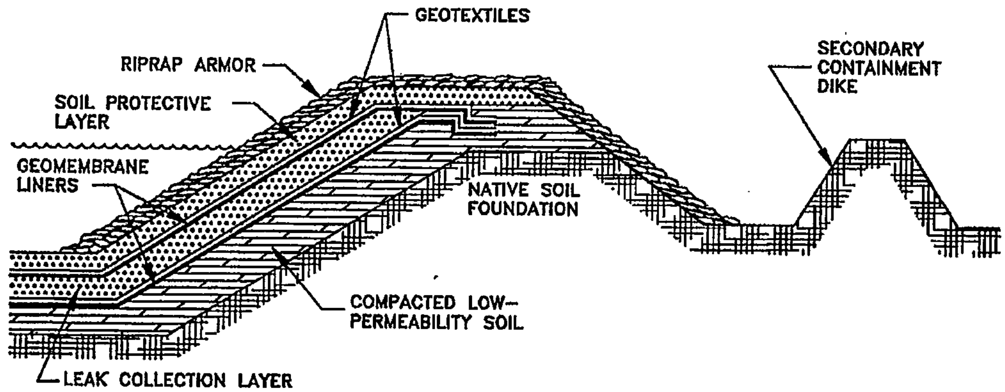
Surface Impoundments

These are basins used to store or dispose of primarily liquid wastes. If the system is planned to be removed after the operating life and the site cleaned of all contamination, then it is considered a storage unit. If the waste is stabilized, the free liquid is removed, and the system is closed and monitored, then it is a disposal unit. Surface impoundments can include liners, leachate collection systems, leachate detection systems, and gas collection systems. If the facility is designed as a disposal unit, then a closure system is necessary.

Under the Federal requirements for the design and operations for surface impoundments (40 CFR 264 subpart K, 264.220 to 264.231) and EPA's design, construction and operation guidelines (Technical Resource Document 530-SW-91-054) (10), a surface impoundment must include the components and elements shown on Figure 1-1. A typical cover profile used when a surface impoundment is closed without waste removal is also shown on Figure 1-2.

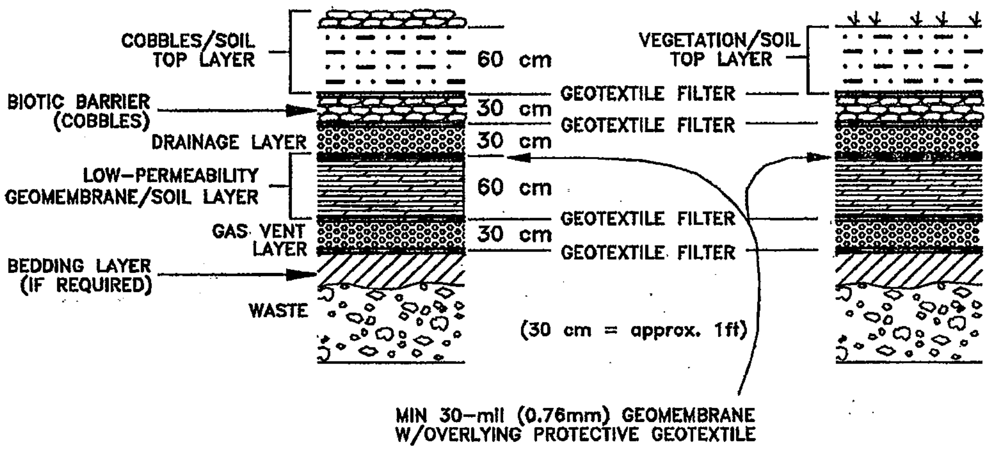
Waste Piles

These are structures in which waste can be treated and/or stored temporarily. A waste pile system must have a similar bottom liner system as the surface impoundment but will not have a final cover since it is only a temporary structure. However, waste piles must be covered by a structure which keeps precipitation, wind and surface water run-on away from the waste. Typically, these protective structures are simple metal buildings, although other protective cover may be used. For example, a geomembrane can be used to cover the waste. The various components and elements of waste piles as required by Federal regulations (40 CFR 264 subpart L, 264.250 to 264.259) are shown on Figure 1-3.



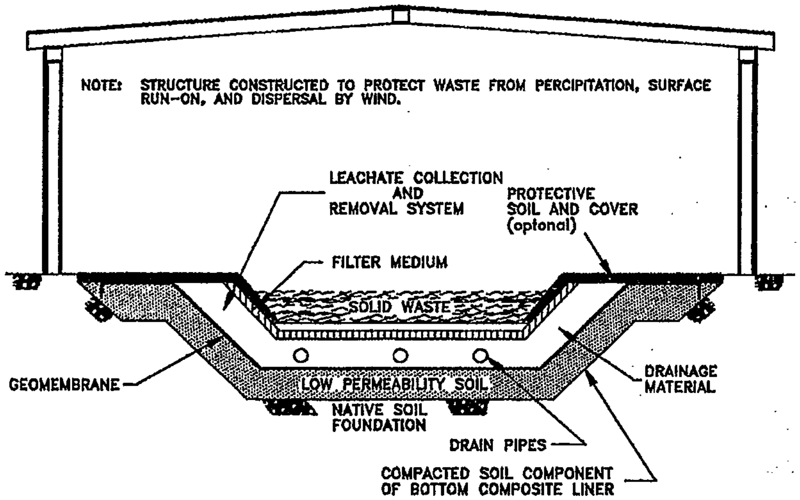
SURFACE IMPOUNDMENT COMPONENTS AND ELEMENTS REFERENCES: 40 CFR 264, SUBPART K TRD/EPA 530-SW-91-054	COMPONENT	ELEMENT
LINER SYSTEM CONSISTING OF ONE OR MORE OF THE FOLLOWING:	●	
• COMPACTED SOIL LINER		●
• BENTONITE MODIFIED ON-SITE SOILS		●
• GEOSYNTHETIC CLAY LINER (GLC)		●
• GEOMEMBRANE		●
LEACHATE COLLECTION SYSTEM or LEAK DETECTION SYSTEM	●	
• GRANULAR SOIL OR GEOSYNTHETIC DRAINAGE LAYER		●
• PIPES,		●
• SUMPS, AND		●
• PUMPS		●
GAS VENTING SYSTEM IF ORGANIC SOILS ARE PRESENT BENEATH THE LINER	●	
• GRANULAR SOIL OR GEOSYNTHETIC DRAINAGE LAYER		●
• VENT PIPES OR FLAPS		●
• GEOTEXTILE FILTER TO PROTECT DRAINAGE LAYER		●
LINER PROTECTION COVER TO PROTECT IT FROM CONSTRUCTION, WEATHER, AND OPERATIONAL DAMAGE	●	
• SOIL OR GEOTEXTILE PROTECTIVE LAYER OVER LINER		●
• STONE OR RIP-RAP ABOVE LIQUID LEVEL TO PREVENT EROSION AND DAMPEN WAVE ACTION		●
SURFACE WATER MANAGEMENT SYSTEM	●	
• DIVERSION DITCHES AND BERMS,		●
• INLETS, PIPES, MANHOLES		●
• AND RETENTION/DETENTION BASINS		●
VOLATILE ORGANIC COUMPOUND EMISSION CONTROL SYSTEM	●	
• COMPLETE ENCLOSURE, E.G. AIR BUBBLE	●	
• SURFACE BARRIER OR FLOATING COVER OF FOAM, OIL, OR GEOMEMBRANE	●	●
• WIND DIVERSION FENCE	●	●
STABLE FOUNDATION	●	●
GROUND-WATER MONITORING WELLS	●	
LIQUID LEVEL CONTROL SYSTEM CONSISTING OF EITHER AN ACTIVE SYSTEM USING PUMPS OR A PASSIVE SYSTEM USING A SPILLWAY	●	
SECONDARY CONTAINMENT SYSTEM SURROUNDING ENTIRE SURFACE IMPOUNDMENT	●	

FIGURE 1-1 SURFACE IMPOUNDMENT USED FOR STORAGE



SURFACE IMPOUNDMENT AND LANDFILL COVER SYSTEM REFERENCES: 40 CFR, SUBPART K TRD/EPA 530-SW-91-054	COMPONENT	ELEMENT
PROTECTIVE COVER WITH VEGETATIVE OR HARDENED EROSION CONTROL SURFACE	•	
• VEGETATIVE LAYER OF TOPSOIL VEGETATION OR		•
• HARDENED LAYER OF RIP-RAP, ASPHALT, OR CONCRETE,		•
• PROTECTIVE SOIL LAYER		•
BIOTIC BARRIER TO LIMIT PENETRATION OF BURROWING ANIMALS AND TAP ROOTS	•	
• COBBLES, STONES OR HARDENED BARRIER SYSTEM		•
• GEOTEXTILE FILTER TO CONTAIN ADJACENT SOILS		•
SURFACE WATER DRAINAGE LAYER	•	
• GRANULAR SOIL OR GEOSYNTHETIC DRAINAGE LAYER		•
• GEOTEXTILE FILTER		•
LOW PERMEABILITY BARRIER CONSISTING OF ONE OR MORE OF THE FOLLOWING	•	
• COMPACTED SOIL LINER		•
• BENTONITE AMENDED ON-SITE SOILS		•
• GEOSYNTHETIC CLAY LINER (GLC)		•
• GEOMEMBRANE		•
GAS COLLECTION SYSTEM IF WASTE WILL GENERATE GAS	•	
• GRANULAR SOIL OR GEOSYNTHETIC DRAINAGE LAYER		•
• VENT PIPES		•
• GEOTEXTILE FILTER TO PROTECT DRAINAGE LAYER		•
BEDDING LAYER OVER WASTE TO PROVIDE STABLE WORKING PLATFORM	•	
• ON-SITE SOIL		•
• GEOTEXTILE FILTER TO PROTECT BEDDING LAYER		•

FIGURE 1-2 COVER SYSTEM FOR SURFACE IMPOUNDMENT/LANDFILL CLOSURE



WASTE PILES FOR INTERIM HAZARDOUS WASTE STORAGE REFERENCES: 40 CFR 264, SUBPART L, 264.250 TO 264.259	COMPONENT	ELEMENT
LINER SYSTEM CONSISTING OF ONE OR MORE OF THE FOLLOWING:	●	
● COMPACTED SOIL LINER		●
● BENTONITE MODIFIED ON-SITE SOILS		●
● GEOSYNTHETIC CLAY LINER (GLC)		●
● GEOMEMBRANE		●
LEACHATE COLLECTION SYSTEM or LEAK DETECTION SYSTEM	●	
● GRANULAR SOIL OR GEOSYNTHETIC DRAINAGE LAYER		●
● PIPES,		●
● SUMPS, AND		●
● PUMPS		●
GAS VENTING SYSTEM IF ORGANIC SOILS ARE PRESENT BENEATH THE LINER	●	
● GRANULAR SOIL OR GEOSYNTHETIC DRAINAGE LAYER		●
● VENT PIPES OR FLAPS		●
● GEOTEXTILE FILTER TO PROTECT DRAINAGE LAYER		●
LINER PROTECTION COVER TO PROTECT IT FROM CONSTRUCTION, WEATHER, AND OPERATIONAL DAMAGE	●	
● SOIL OR GEOTEXTILE PROTECTIVE LAYER OVER LINER		●
● STONE OR RIP-RAP ABOVE LIQUID LEVEL TO PREVENT EROSION AND DAMPEN WAVE ACTION		●
SURFACE WATER MANAGEMENT SYSTEM	●	
● DIVERSION DITCHES AND BERMS,		●
● INLETS, PIPES, MANHOLES		●
● AND RETENTION/DETENTION BASINS		●
VOLATILE ORGANIC COUMPOUND EMISSION CONTROL SYSTEM	●	
● COMPLETE ENCLOSURE, E.G. AIR BUBBLE	●	
● SURFACE BARRIER OR FLOATING COVER OF FOAM, OIL, OR GEOMEMBRANE	●	●
● WIND DIVERSION FENCE	●	●
STABLE FOUNDATION	●	●
GROUND-WATER MONITORING WELLS	●	
LIQUID LEVEL CONTROL SYSTEM CONSISTING OF EITHER AN ACTIVE SYSTEM USING PUMPS OR A PASSIVE SYSTEM USING A SPILLWAY	●	
SECONDARY CONTAINMENT SYSTEM SURROUNDING ENTIRE SURFACE IMPOUNDMENT	●	

FIGURE 1-3 WASTE PILE USED FOR INTERIM WASTE STORAGE

Landfills

These are final disposal units for solid and hazardous wastes. Landfills have the same components and elements as the surface impoundment disposal units. Under the requirements for the design and operation of landfills (40 CFR 264 subpart N, 264.300 to 264.317) and the design, construction and operations guidelines presented in EPA seminar publications (11, 12), a landfill should include the components and elements shown on Figure 1-4.

On-Site Waste Isolation

Remedial actions to isolate uncontrolled releases of contaminates are described in 40 CFR 300 "Appendix D - Appropriate Actions and Methods of Remediating Releases." Waste isolation systems include caps built over waste to minimize infiltration of rainwater, and both horizontal barriers under the waste and vertical barriers at the lateral extent of the waste to prevent uncontrolled release of leachate (12, 13, 14). These are systems which are constructed on remediation sites to isolate and allow for the treatment of an uncontained waste.

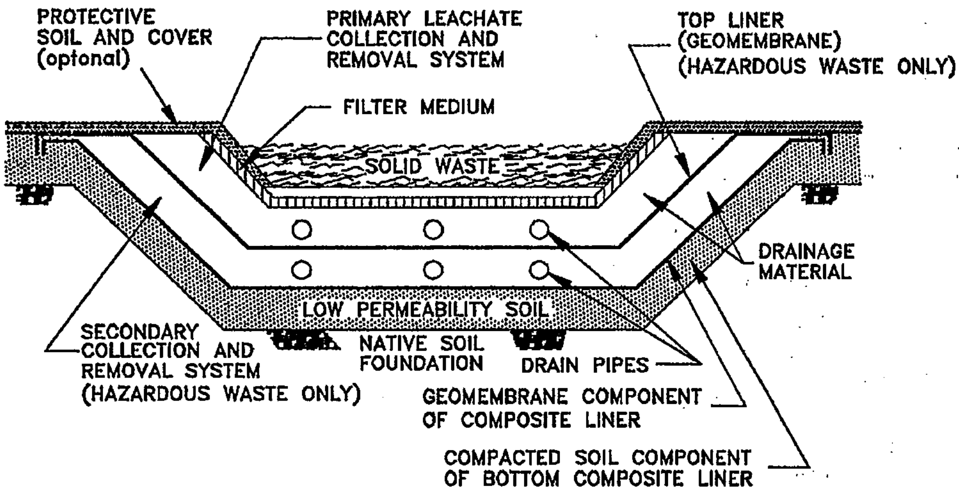
Caps --

Waste facility caps reduce water infiltration, control gas and odor emissions, improve the aesthetics, and provide a stable surface over the waste. A composite barrier capping system (Figure 1-2), is required for the closure of hazardous waste storage facilities (12, 13). A hardened cap is typically required in an arid climates where a vegetative cover will not survive, in urban areas where vegetation may be undesirable, or at industrial facilities where it would be advantageous to continue using the site. The hardened cap integrates the vegetative layer, protective layer (biotic) and drainage layer into one layer as shown in Figure 1-5. The hardened cap can be constructed using "hard" elements, such as graded stone, asphalt, or concrete. Note that the use of a hardened surface layer does not eliminate the need for the geomembrane/clay moisture barrier components in the cap.

Horizontal Barriers --

Horizontal barriers are installed below an existing waste mass to contain the waste and prevent the movement of contaminate into the surrounding soil and water. Horizontal barriers are very difficult to inspect due to the overlying waste.

Horizontal barrier techniques involve the injection of grout under the waste using one of the following methods:



LANDFILLS – LONG–TERM HAZARDOUS WASTE DISPOSAL REFERENCES: 40 CFR 264, SUBPART N EPA 625/4–91–025, EPA 625/4–89–022	COMPONENT	ELEMENT
LINER SYSTEM CONSISTING OF ONE OR MORE OF THE FOLLOWING:	•	
• COMPACTED SOIL LINER		•
• BENTONITE MODIFIED ON–SITE SOILS		•
• GEOSYNTHETIC CLAY LINER (GLC)		•
• GEOMEMBRANE		•
LEACHATE COLLECTION SYSTEM or LEAK DETECTION SYSTEM	•	
• GRANULAR SOIL OR GEOSYNTHETIC DRAINAGE LAYER		•
• PIPES,		•
• SUMPS, AND		•
• PUMPS		•
GAS VENTING SYSTEM IF ORGANIC SOILS ARE PRESENT BENEATH THE LINER	•	
• GRANULAR SOIL OR GEOSYNTHETIC DRAINAGE LAYER		•
• VENT PIPES OR FLAPS		•
• GEOTEXTILE FILTER TO PROTECT DRAINAGE LAYER		•
LINER PROTECTION COVER TO PROTECT IT FROM CONSTRUCTION, WEATHER, AND OPERATIONAL DAMAGE	•	
• SOIL OR GEOTEXTILE PROTECTIVE LAYER OVER LINER		•
• STONE OR RIP–RAP ABOVE LIQUID LEVEL TO PREVENT EROSION AND DAMPEN WAVE ACTION		•
SURFACE WATER MANAGEMENT SYSTEM	•	
• DIVERSION DITCHES AND BERMS,		•
• INLETS, PIPES, MANHOLES		•
• AND RETENTION/DETENTION BASINS		•
WIND DISPERSAL CONTROL SYSTEM	•	
• COMPLETE ENCLOSURE, E.G. AIR BUBBLE	•	
• SURFACE BARRIER OF FOAM OR GEOMEMBRANE		•
• WIND DISPERSION FENCES		•
STABLE FOUNDATION	•	•
GROUND–WATER MONITORING WELLS	•	
LIQUID LEVEL CONTROL SYSTEM CONSISTING OF EITHER AN ACTIVE SYSTEM USING PUMPS OR A PASSIVE SYSTEM USING A SPILLWAY	•	
SECONDARY CONTAINMENT SYSTEM SURROUNDING ENTIRE SURFACE IMPOUNDMENT	•	

FIGURE 1-4 LANDFILL USED FOR HAZARDOUS WASTE STORAGE

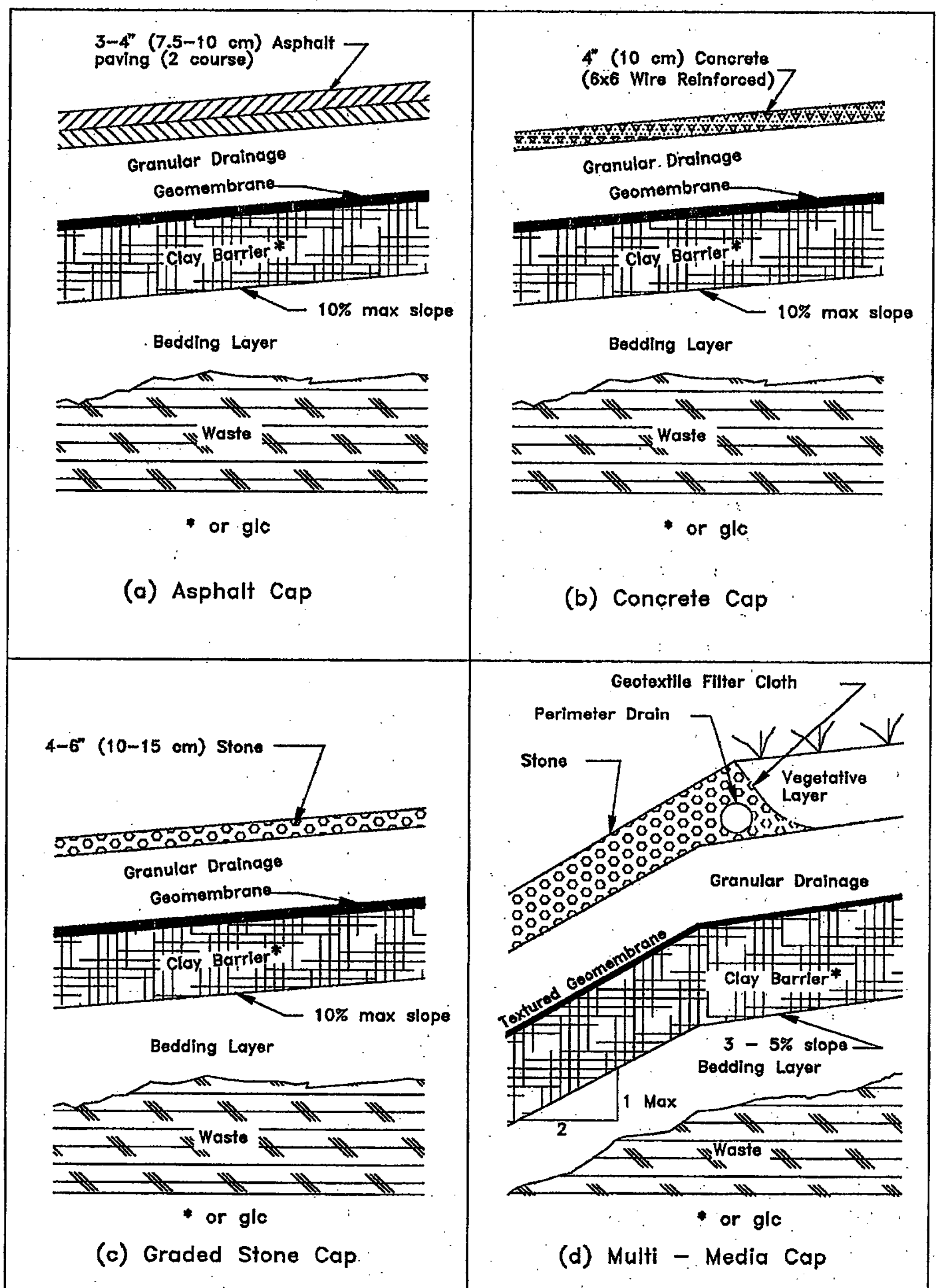


FIGURE 1-5 HARDENED CLOSURE SYSTEM

- vertical borings drilled through the waste and pressure injection or rotary jetting of the grout beneath the waste,

- horizontal borings drilled below the waste from trenches and pressure injection of the grout beneath the waste,

- block displacement method which surrounds the waste with a vertical grout wall and then injects low pressure grout beneath the waste. The entire waste block is raised in this process (15).

All of these methods require that the borings be spaced close enough together that the grout bulbs or lenses overlap and form a continuous barrier. Verification of the overlap is critical but very difficult. Potential inspection methods are limited to test excavations, exploratory borings, and observed impact on ground water if the barrier is placed beneath the ground water table.

Vertical Barriers --

Vertical barriers are wall-like systems used to isolate any contaminates that have leached from the waste and that are moving laterally. To be effective, these barriers should intercept a continuous impervious horizontal layer below the waste. This bottom layer can be a naturally occurring layer such as an aquiclude, or a horizontal barrier. Several types of vertical barriers are commonly used, including:

- <u>Slurry wall</u>. A trench surrounding the waste, filled with a soil bentonite and/or concrete-bentonite slurry.

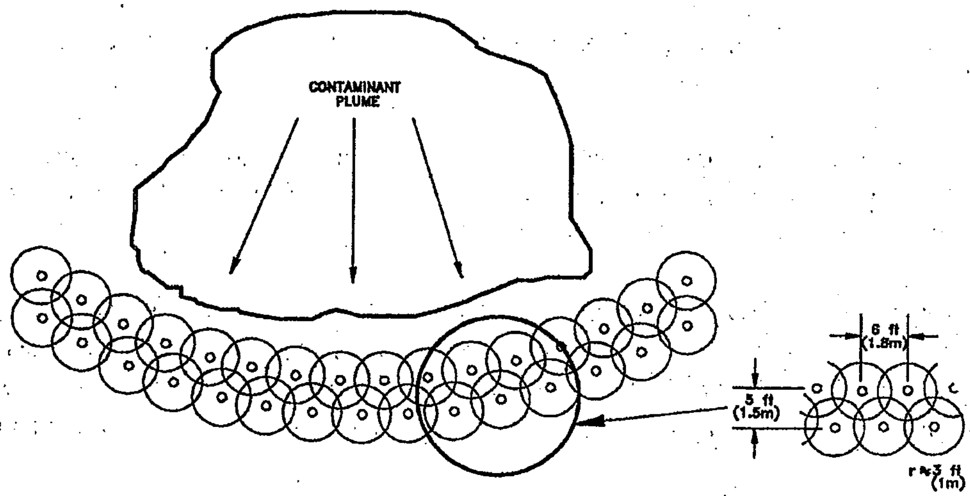
- <u>Grout curtain</u>. Grout is injected in a series of vertical columns that surround the waste, creating a continuous curtain.

- <u>Geomembrane curtain</u>. Interlocking geomembrane panels are placed in a vertical trench surrounding the waste. In some cases the geomembrane is used in conjunction with the slurry wall to form a composite liner system.

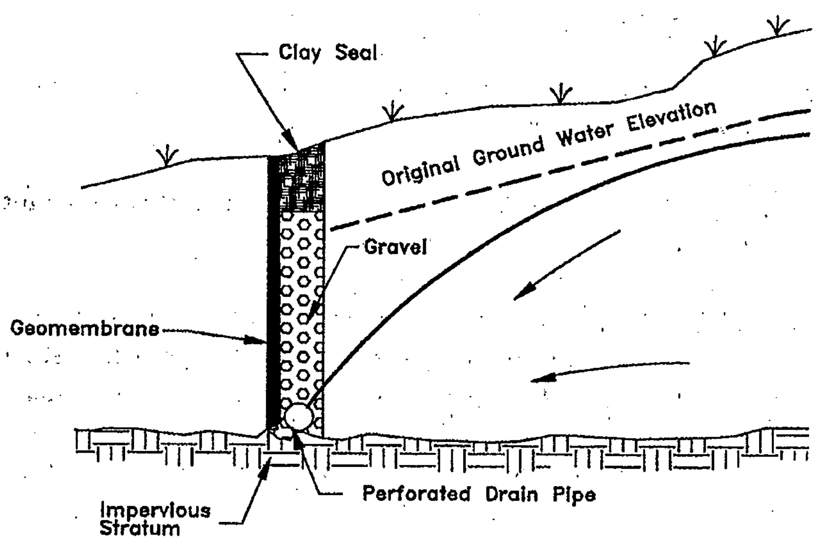
Schematics of grout curtains and geomembrane curtains are shown in Figure 1-6.

1.3 Components and Elements in Waste Containment Systems

The regulatory waste containment systems reviewed in Section 1.2 are constructed using a small family of functional components. These functional components include:



a. GROUT CURTAIN VERTICAL BARRIER



b. GEOMEMBRANE VERTICAL BARRIER

FIGURE 1-6 VERTICAL BARRIER SYSTEMS

- Hydraulic Barriers
- Hydraulic Conveyances
- Filter Layers
- Erosion Control Layers
- Protective Layers
- Earthwork

Each of these basic building blocks is in turn composed of distinct physical elements as listed on Table 1-1. It is important to understand that project specifications and the construction quality management program will focus on elements and not components. Thus project specifications for a hydraulic barrier will provide guidance for clay or geomembrane properties but will not identify functional properties of the overall hydraulic barrier. This document therefore examines construction quality management at an elemental level.

TABLE 1-1 WASTE CONTAINMENT COMPONENTS AND ELEMENTS

COMPONENT	ELEMENTS

Hydraulic Barriers	Geomembranes
	Geomembrane Interlocking Panels
	Grouts
	Compacted Soil
	Bentonite Products
	    Soil-Bentonite Blends
	    Geosynthetic Clay Liner
	    Bentonite Slurries
	    Concrete/Bentonite Slurry

Hydraulic Conveyances (Both Liquid and Gas Conveyance)	Natural Sand/Gravel Drain/Collector Geosynthetic Drain/Collector Pipe Sumps Pumps
Filter Layers	Sand/Gravel Filter Geotextile
Erosion Control Layers	Stone and Rip-Rap Vegetation and Topsoil Geosynthetic Erosion Control Products
Protective Layers	Hardened Layer Biotic Layer Geotextile Soil Layer
Earthwork	Soil Foundation or Bedding Layer Soil Embankments Geotextile Separator

1.4 References

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SECTION 2.0

Summary of Construction Elements and Key Properties

Construction elements are commonly used as pay units on construction projects and as such are readily identified. For example, the contractor may be paid based on the square footage of geomembrane installed or the cubic yardage of compacted clay, sand, etc. installed. Specific references to these elements are made in the project specifications.

This chapter reviews the elements common to components used in waste containment systems. Each element will have physical properties defined in the project specifications. Some of these properties must be verified in the field as part of the construction quality management program. However, many of the physical, mechanical and chemical properties cannot be verified in the field. In these cases, the construction quality management program must rely either on certification by the manufacturer or supplier that the material meets project specifications or conformance testing by an independent laboratory. Key properties or installation parameters that require verification and corresponding test methods are discussed in this chapter. Standard test methods to quantify material properties are identified in Appendix A.

2.1 Hydraulic Barriers

A site manager should realize that the performance of a barrier system can exceed the sum of the elements that comprise it. A well constructed composite liner system, for example, will have less infiltration than what is expected from independent evaluations of the clay liner and geomembrane. Such synergistic interaction between elements is not accounted for in project specifications or the construction quality management program. Table 2-1 identifies hydraulic barrier systems and elements that require field testing.

Geomembranes

Geomembranes are used as low permeability barriers in both the bottom liners and caps of waste containment systems. In a hazardous waste landfill, geomembranes can be used alone as the upper or primary liner, and in conjunction with a low permeability soil layer to form the lower or secondary composite liner. Manufacturers and fabricators of geomembranes are responsible for the quality control of both the raw materials, such as plastic resin, and the finished sheets. Their internal quality control (QC) incorporates routine testing of the polymer and the finished product. Test results must be submitted with each lot of geomembranes shipped to the site. In addition, certification must be presented with the geomembranes

TABLE 2-1 BARRIER SYSTEM ELEMENT TESTING/INSPECTION

ELEMENT	MATERIAL PROPERTIES/POST-CONSTRUCTION CARE	TEST	INSTALLATION QUALITY VERIFICATION	FIELD TEST
Geomembrane	- Polymer properties:		* Placement Considerations	
	- Melt Flow Index	ASTM D1238	- Preparation of surface, E.G. no sharp items, rocks, etc.	Visual
	- Carbon Black Content	ASTM D1603	- Stable foundation	Proof Roll
	- Carbon Black Dispersion	ASTM D3015	- Anchor trenches have proper dimensions and location	Survey
	- Environmental Stress Crack	ASTM D1693(c)	- Geomembrane panels placed per panel placement drawing	Visual
	- Notched Constant Load Test	GRI GM5	- Measure overlap of seams	Visual
	- Mechanical Properties		* Seaming	
	- Thickness	ASTM D751	- Adequate surface preparation; clean, dry, extent grinding	Visual
	- Density	ASTM D792 (A - 1)	- Temperature, Pressure, Speed of Seaming	Certification
	- Tensile Properties	ASTM D638 (IV)	- Adequate curing time prior to testing (if applicable)	Visual/Trial
			- Document start & stop locations, crews, repairs and weather	Visual
	Post Construction: Upon completion, the geomembrane should be covered or weighted using sandbags to prevent damage from wind. Additionally, the geomembrane is vulnerable to construction and weather related damage if left exposed.		- 100% Non-destructive seam testing: Air lance, Mechanical Point Stress, Electric Spark, Vacuum Chamber, Dual Seam	Per Spec.
			- Destructive Seam Testing: Peel(ASTM D413), Shear(ASTM D882) or ASTM D3083 - 1" Wide	Per Spec.
Geomembrane Interlocking Panels	* Polymer Properties of Geomembrane (As Above)	As Above	* Placement Considerations	
	* Interlock Sealing Element	Certification	- Adequate depth of placement(slurry trench or vibration)	Visual
	* Mechanical Properties of Geomembrane(As Above)	As Above	- Interlock panels placed per panel location drawing	Visual
			- Continuous seaming of interlock seal	Visual
	Post Construction: Verification of the integrity of the interlock seal is difficult. No known field verification strategies		* Seaming	
			- Pressure of interlock seaming element	Visual
Grouts	* Grout Material Properties:		* Placement Considerations	
	- Viscosity of Grout	ASTM D4016	- Spacing of drill pipe used to inject grout	Visual
	- Gradation of Sand	Certification	- Depth of drill pipe during injection	Visual
	- Unit Weight	ASTM D4380	- Quantity of grout injected	Bulk Measure
	- Compressive Strength	ASTM D4832	- Pressure of grout during injection	Visual
Bentonite Amended Soil (Also Bentonite Slurry) (Also Cement-Bentonite)	* Bentonite Material Properties: Bentonite Type,		* Placement Consideration	
	Atterburg Limits, Percent Impurities	Certification	- Thoroughness of blending, e.g. % Bentonite	Methylene Blue
	* Soil Properties: Grain Size Distribution	ASTM D422	(May require Pugg Mill or Asphalt Grinder for	
	Atterburg Limits	ASTM D4318	a uniform mixture of soil and Bentonite)	
	* Bentonite Amended Soil: % Bentonite	Methylene Blue		
	Water Content	ASTM D4959		
	Post Construction: Same as Clay Below			
Geosynthetic Clay Liner (GCL)	* Bentonite Properties: Atterburg Limits, Type	ASTM D4318	* Placement Consideration	
	Percent Impurities, Mass per Unit Area of Board	Certification	- Minimum 6-inch overlap of adjacent panels	Visual
	* Geotextile Properties: AOS, Trap Tear, Polymer	Certification	- Subgrade free of rocks, ruts, ets. that could	
	Post Construction: Protect from free water		penetrate board	Visual
			- Stable foundation	Proof Roll
Compacted Clay Liner (CCL)	* Clay Properties: Atterburg Limits	ASTM D4318	* Placement Considerations	
	Grain Size Distribution	ASTM D422,	- Soil water content as specified	ASTM D4959
	Moisture-Density Relationship	ASTM D1557 or D698	- Soil density as specified	ASTM D2922
	Maximum Clod Size < 2 inch	Visual	- Water content adjustment not made 24-hr. prior to placement	Visual
	Post Costruction: Clay liners can be damaged from either dessication or freezing. Soil liner must be protected from drying or freezing		- Sheepsfoot roller with fully penetrating feet	
			- Scarify between lifts	

stating that the materials are in compliance with manufacturer's published information and/or the project specifications.

A sample of each lot (production run) of geomembrane material that arrives at the site should be taken. Tests on these samples should confirm that they have the same polymer properties required by project specifications. This is known as *conformance testing* and should be performed by an independent laboratory. A series of samples, instead of one, may be necessary to provide all responsible parties with a sample. Testing of the geomembrane in the field is typically limited to verification of membrane thickness, visual inspection for physical defects, and a thorough testing of all field seams.

Non-Destructive Testing (NDT) of seams is required for the entire length of the seam. Such testing is performed using the vacuum box test for single bonded seams or the pressurized air channel test for those seams that have two lines of bonding separated by an air channel. The vacuum box test applies a moderate vacuum to a seam previously wetted with soapy water. Leaks are indicated by bubbles. The test must be repeated over the entire length of the seam. The pressurized air channel test inflates the seam and checks for a loss of pressure. Samples for destructive testing are commonly taken at a minimum of every 500 feet of seam, with at least one sample taken per seam. Additionally, samples must be cut at least every four hours or when seaming conditions change to provide samples for destructive testing and to monitor variations in seam quality due to variations in operator or seaming equipment. The reader is referred to the Technical Guidance Document EPA/530/SW-91/051 entitled "Inspection Techniques for the Fabrication Geomembrane Field Seams. Specific test requirements may be part of the Construction Quality Assurance Manual prepared for the project.

Geomembrane Interlocking Panels

Geomembrane interlocking panels are installed in vertical trenches to construct a low permeability barrier. The panels consist of membrane panels that connect along their lengths much like conventional steel sheet piles. The panels are pre-fabricated and assembled at the site by locking the panels together and placing them into the trench.

Geomembrane interlocking panels have two physical elements; high density Polyethylene (HDPE) panels with interlock fittings along their vertical edge, and a soft plastic sealing medium within the interlock that provides a hydraulic seal to the interlock fittings. The HDPE interlock closely resembles that used in conventional steel sheet files: A female channel on one panel that engages a male edge of an adjacent panel. Field inspection of the HDPE panels and hydraulic seal material is generally identical to that required for geomembrane materials. Field testing of the geomembrane panels is typically limited to verification of panel thickness. The interlock seal material is hydrophilic and swells in the presence of the groundwater to establish a seal. The manufacturer should be required to provide certification of the long-term chemical stability of the hydraulic seal material when exposed to the site-specific contaminant.

Geomembrane interlocking panels can be installed in open trenches, slurry trenches, or vibrated into sandy soils using a steel mandrel. Care must be taken to insure that the hydraulic interlock and seal material properly seat along the entire length of the interlock channel. This verification can be difficult in slurry wall and vibrated installations. The continuity of the interlock is tested during installation of a new panel using a "runner". The runner consists of a 3 1/2 inch section of the female portion of the interlock that is secured to a rope. The runner is installed ahead of the panel to be installed so that it is pushed down the interlock by the panel being installed. The rope is knotted to show final installation depth. If the runner comes to a halt before the full insertion depth is reached, the panel must be removed and redriven. The hydraulic seal is marked in a similar manner and is not accepted if the seal advance depth is less than 85% of the panel depth.

Grouts

The grout used in a waste containment system is usually a mixture of cement and bentonite. Grouts are, however, available with silica, acrylate, urethane, and Portland cement binders. Grout can be injected in horizontal or vertical borings using a variety of pressures. The suppliers of the grout materials must provide material property data sheets and a certification that the materials conform to their specifications. During the mixing of the grout, the quantities of materials used in the mix should be measured and recorded. Once the grout is mixed, it must be tested to confirm that it meets project specifications for viscosity (Marshal funnel test), setting time, and strength.

Grout is pressure injected into the ground by specialty contractors. Field monitoring requirements include documentation of the injection location, depth, pumping rate, and total grout volume used (see Table 2-1).

Bentonite Products

Bentonite provides an effective moisture barrier. Available as either sodium bentonite mined in several western states or a less active calcium bentonite from Georgia, commercial bentonite is purchased in powder or pellet form. The permeability of bentonite ranges from 10^{-8} cm/sec for calcium bentonite to as low as 10^{-10} cm/sec for sodium bentonite. Bentonite can be used by itself to form a moisture barrier or blended with on-site soils to form an acceptable soil liner. Bentonite is available from commercial suppliers who must provide a summary of the material properties of the bentonite shipped to the project site and certification that the materials meet their specifications.

Bentonite Amended Soil--

When there is not an adequate supply of low permeability soil on site for the construction of a soil barrier layer, a bentonite soil amendment can be used to lower the permeability of the on-site soils. Typically, a 3 to 6% bentonite amendment by dry weight is sufficient to achieve a permeability of 1 x 10^{-7} cm/sec using on-site soils. Sands, however, may require as much as 10 to 15% bentonite amendment. The percent bentonite required is evaluated in the laboratory using site specific soils. Project specifications are then prepared to ensure that the soil and the bentonite used in the field replicate that used in the laboratory. Once the bentonite is mixed with the soil, it should be tested to evaluate the thoroughness of the mixing and the concentration of the bentonite (12). A uniform mixing of bentonite is essential to the performance of the soil-bentonite liner. This mixing may require a pug mill or asphalt pavement surfacer to adequately blend the bentonite with on-site soils.

The installation methods and evaluation of the bentonite soil liner is the same as that for an unamended clay liner. If the bentonite is mixed with the soil in place using a disk, careful visual observation of the depth of mixing and the coverage of the bentonite over the liner area must be made.

Geosynthetic Clay Liner (GCL)--

A GCL is essentially a pre-fabricated low permeability soil layer. The bentonite is usually sandwiched between two geotextiles or adhered to a geomembrane. GCL's are manufactured in 8 ft. and wider sheets and are shipped to the site in rolls. Typically the weight of bentonite (or bentonite and adhesive) per square foot is specified and must be field verified.

The GCL barrier is installed by simply unrolling the sheets over a prepared subgrade. The subgrade should be free of large rocks, ruts, and objects that could penetrate through the GCL. Additionally, the subgrade must be stable, which can be checked by proof-rolling. Seaming of the GCL barrier is typically limited to a minimum 6-inch overlap of adjacent sheets. The water seal at the seam forms when the bentonite hydrates and "oozes" out from between the geotextiles. Additional dry bentonite powder may be spread between the overlaps to improve the seal.

Bentonite Slurries--

Bentonite slurries are used in vertical barrier walls to displace the natural soils and construct a low permeability barrier. Bentonite slurries are mixtures of 4 to 7% bentonite and water. Quantities of materials used in the mix should be measured and recorded. After the mixing, the bentonite slurry should be tested for gel strength using a Fann Viscometer. Typical gel strengths exceed 15 psf (240 kg/m^2).

The bentonite slurry can be used "as is" to prevent the collapse of cut-off wall excavations or blended with on-site soils to form a soil-bentonite slurry used in permanent barrier walls. The soils should have 20-40% fines and are blended with the bentonite slurry until a paste is formed. This paste should have the consistency of fresh mortar or concrete and flow easily.

Slurry uniformity is poor when dozers are used to blend the soil and bentonite. If dozers are used, increased visual inspection and bentonite concentration testing may be required.

Concrete-Bentonite Slurries--

Concrete-bentonite slurries are used on sites where adequate soils to form soil-bentonite slurries are not available or when increase strengths are needed. The concrete-bentonite slurries are mixtures of approximately 18% concrete, 6% bentonite, and 76% water. The concrete bentonite slurry is similar to the bentonite slurry above and the test methods used in that section also apply to this material.

Because of the concrete, the concrete-bentonite slurry will hydrate and begin setting in 2-3 hours. The installation must be monitored to ensure that the slurry has not hydrated prior to placement.

Compacted Clay Liners (CCL)

A CCL may be used as the primary moisture barrier in both waste liner and cover systems. Achieving a low permeability in a clay liner requires a suitable clayey soil and proper preparation and compaction of the soil. Test data (4,11) clearly demonstrate that the permeability of a clay liner can be increased 100 to 1000 times if a single parameter in preparation or compaction is neglected. Soil selected for use as a clay liner is specified using soil plasticity (Atterburg Limits) and grain size distribution. Both parameters can be easily monitored during actual field placement of the liner.

Construction of a clay liner requires proper soil preparation and correct compaction equipment and technique. Soils used for clay liners should be processed to ensure that the soil water content is as specified, the soil clods are no larger than 1 to 2 inches, and the maximum particle size is less than required by the project specifications. For composite liners, the maximum rock size in the last lift is frequently less than 1.0 inch (2.54 cm) to minimize potential damage from rocks to the overlying geomembrane. Liner soil preparation is usually done as the soil liner material is placed in a stockpile. Significant moisture adjustment should not be attempted in the 24 hours preceding placement of the soil.

Key construction guidelines for installing clay liners are related to both equipment and operations. Compaction equipment must have feet that penetrate completely through a loose layer of fill. Alternately, the loose lift thickness can be adjusted to maximize the efficiency of the available compaction equipment. Compacted effort (compactor speed and number of passes) should be consistent with the minimum effort established in a test strip. Additionally, bonding between the layers of compacted clay must be enhanced by scarifying the surface of the previous lift. The as-built clay liner must be tested to verify that it meets project compaction criteria. This requires a field sampling program to measure soil moisture content and density.

A clay liner is very susceptible to damage due to either desiccation or freezing. Clay liners left exposed must be protected from desiccation using a surface sealant (acrylic sprays or light membranes) or an additional layer of "sacrificial" soil. Soil cover also serves to prevent freezing of the clay liner. Even a single cycle of freezing can significantly increase the permeability of a clay liner. Testing a suspect soil liner for permeability requires either a large-scale double-ring infiltrometer test or laboratory testing of undisturbed (UD) samples taken from the soil liner.

2.2 Hydraulic Conveyances (Both Liquid and Gas)

Drainage layer components are designed to collect leachate beneath the waste or to collect gas above the waste. Both functions require the drainage layer to be significantly more permeable than the adjacent waste or soils. Thus filter systems, discussed in Section 2.3, are required with all drainage systems. Newer geocomposite systems provide both the drainage media and filter layer in a single commercial product. Field testing requirements for hydraulic conveyance systems are presented on Table 2-2.

Natural Drains and Collectors

A sand or gravel drainage layer can be used as part of the leak detection component of a waste containment system, as the primary drainage layer above the bottom liner, and as an infiltrating storm water drain in the capping system. Soil drains provide a high permeability medium into which liquids can easily drain to a network of collection pipes. The soil drain usually consists of clean sand or gravel sorted to specific particle sizes by a quarry. In some cases suitable sands or gravels are found on site, but this is unusual.

TABLE 2-2 HYDRAULIC CONVEYANCE SYSTEM ELEMENT TESTING/INSPECTION

ELEMENT	MATERIAL PROPERTIES/POST CONSTRUCTION CARE	FIELD TEST	INSTALLATION QUALITY VERIFICATION	FIELD TEST
Sand/Gravel/Drain Collector	- Material Properties: Natural Water Content Grain Size Distribution Laboratory Hydraulic Conductivity Moisture-Density Relationship	ASTM D2216 ASTM D422 ASTM D2434 ASTM D1557 or ASTM D698	* As Placed Properties - Water Content - In-Place Density - Lift Thickness	 ASTM D2216 ASTM D2922 Visual
	Post Construction: Natural drainage layers must be protected from fines related to sedimentation		* Visual observation of compactive effort as measured by number of passes with a given compaction equipment	Visual
Geosynthetic Drain/ Collector	- Material Properties: Weight per sq. foot, transmissivity under load, polymer properties (see geomembrane)	Certification	* Placement Considerations - Measure width of panel overlap - Avoid folds, wrinkles, or damage to panels - Provide temporary anchorage, e.g. sandbags	 Visual Visual Visual
	Post Construction: Geosynthetic drainage layers must be protected from damage by direct trafficking of vehicles, and movements caused by wind or man.			
Pipes	- Material Properties: Polymer properties, pipe rating - Mechanical Properties: Wall thickness and diameter	Certification per ASTM D1248 Visual	* Placement Considerations - Verify pipe perforations, placement, and connectors in perforated pipe - Verify location and grade of pipe - Hydrostatic pressure test solid pipe joints - Verify bedding material satisfies specifications * Grain Size Distribution In-Place Density	 Visual Survey See Pipe Manual 'Butt Fushion' Visual ASTM D422 ASTM D2922
	Post Construction: Pipes must be protected from damage by direct traffiking of vehicles, and movements prior to burial.			
Sumps	- Material Properties: Polymer properties (see geomembrane) - Mechanical Properties (prefabricated sump) * Diameter and wall thickness * Pipe penetrations per specs.	Certification Visual Visual	* Placement Considerations - Subgrade perpared free of rocks or sharp objects - Bedding layer required for prefabricated sumps - Verify location and grade of sump * Seaming (see geomembrane)	 Visual Visual Survey
Pumps	- Mechanical Properties * Flow Rating	Certification	* Placement Considerations - Installation per manufacturer's recommendation	Visual
	Post Construction: Verify rated capacity with hydro test			

Drain materials are specified using a particle size distribution and samples should be taken for laboratory grain size and permeability conformance testing. Soil drains typically require only moderate to light compaction and the as-installed drain layer thickness should be verified. Natural drainage layers must be protected by diversion berms or geotextiles from the introduction of water borne fines from surface erosion of adjacent slopes.

Geosynthetic Drains and Collectors

A geocomposite drain consists of a core material that provides a pathway for drainage and a surrounding geotextile that prevents clogging of the core. Geocomposite drains can be used as part of the leak detection component of a waste containment system, as the primary drainage layer above the bottom liner, and as a lateral drain in the capping system. Similar to the soil drain, a geocomposite drain provides a high transmissivity core through which liquids can easily drain into a network of collection pipes. Geocomposite drains are pre-fabricated and come in rolls or panels up to 300 ft. in length.

Geocomposite drains are available from suppliers who must certify that the materials supplied meets the manufacturer's minimum specifications. The CQA officer must compare the manufacturer's specifications with the project specifications. Laboratory conformance testing should be performed on the drains under service conditions if differences exist between the two specifications. The material delivered to the site should be inspected for general compliance with project specifications and to check for damage during shipping.

Installation of the geocomposite drain requires no field testing. The drain should be inspected to confirm that it is installed according to manufacturer's and project specifications. Overlaps between adjacent roll ends or panels are particularly important with the proper overlap length, orientation, and plastic ties used to bind the overlap. Geosynthetic drainage layers must be protected from damage by vehicle traffic, wind or other disturbances. The layer should also be protected from fines carried by surface erosion during construction.

Plastic Pipes

Both perforated collection and solid transmission pipes are used in the leak detection systems, the primary leachate collection drain, the lateral drain in the cap, and to carry stormwater and leachate away from the waste containment system. Collection and transmission pipes are constructed from a variety of plastics and can be designed for gravity flow lines as well as low or high pressure lines, depending upon the application.

Collection and transmission pipes are available from suppliers who must certify that the materials meet manufacturer's specifications. The material delivered to the site should be inspected for general compliance with the project specifications and to check for damage during shipping.

Installation of collection and transmission pipes should be field inspected to verify that the location and grades of the pipe and joints, and the bedding material and backfill meet project specifications. Perforated pipes require additional inspection of the perforations (hole diameter and spacing) and pressure pipes require hydrostatic pressure testing (see Appendix A).

Sumps

Leachate sumps are located in both the primary leachate collection layer and the bottom/lower leak detection layer. Sumps are located at low points in the liner and act as basins in which the leachate can be collected. From the sumps, the leachate is either drained out of the waste containment system by gravity or pumped out. The sumps can be a simple depression in the composite liner or a pre-manufactured plastic basin that is set in the clay liner so that its top is flush with the geomembrane liner. The geomembrane is fusion-welded to a flange on the upper edge of the sump. Pre-manufactured sumps eliminate difficult-to-test field seams or complex grading.

If leachate sumps are fabricated on site, then they will be made from the same materials as the liner system, so certification of the liner materials will already have been provided. If the leachate sumps are pre-fabricated then the supplier must certify that they meet project specifications. The sumps delivered to the site should be inspected for general compliance with the project specifications and any damage.

Sumps are the only area of a waste containment system that will continuously receive leachate. As such, any defect in the sump may result in a continuous long-term leak. The seams made at this location are difficult to test due to their short length and tight angles. Destructive samples should be kept to a minimum due to the difficulty of repairs in the vicinity of the sumps.

Pumps

The leachate can be drained by gravity from the waste containment system or it can be pumped out the system using a submersible pump. The pumps used to move leachate are manufactured for harsh environments and can be powered by electricity or compressed air. Leachate pumps are available from suppliers who must certify the pumps meet the manufacturer's specifications. The pumps should be inspected when delivered to the site to confirm that they were not damaged during shipment.

Installation of the pumps should be done in accordance with the manufacturer's instructions. All electrical connections, power requirements, insulation, grounding, and piping should be installed and used as specified by the manufacturer. These items should be inspected during installation to verify that they follow the manufacturer's recommendations. The pump should be tested, using water, to verify that it is working properly.

2.3 Filters

Filter layers must provide for long-term movement of water through the layer while at the same time limit the movement of waste or soil particles across the layer. Too tight a filter will quickly clog while too loose a filter will result in an excessive loss of solids through the filter. Biological growth can also impact filter layer performance and is currently being studied by the EPA. Field verified material properties and installation factors are given in Table 2-3.

Sand/Gravel Filter

A soil filter is used to prevent very fine soil and waste particles from entering into a drain, accumulating, and eventually clogging the drain. Typically, soil filters consist of sand and/or gravel which has been screened to a specified particle size. The sand/gravel filter should have a particle size smaller than the drain particle but larger than the infiltrating particle. The filter may consist of one layer or several successively graded layers depending upon the performance objectives of the designer. A soil gradation requirement will be provided for each sand/gravel filter layer in the project specifications.

The sand and gravel filter should be laboratory tested to ensure that the grain size distribution meets the project specifications. Individual filter layers are also field tested to ensure that the installed filters meet compaction and thickness specifications.

Geotextile Filter

A geotextile filter is used to prevent very fine soil and waste particles from entering into a drain, accumulating and eventually clogging the drain. The geotextile filter is selected by the designer based on its opening size and permittivity. Suppliers of geotextile filters must certify that the materials meet the published manufacturer's specifications. Published manufacturer specifications must also satisfy the specific geotextile specifications for the project. Conformance testing of the geotextile is recommended for critical filter applications (see Table 2-3). The geotextile arrives on the site in rolls for installation. The material delivered to the site should be inspected to ensure compliance with the project specifications and to check for damage during shipping.

TABEL 2-3 FILTER SYSTEM ELEMENT TESTING/INSPECTION

ELEMENT	MATERIAL PROPERTIES/POST CONSTRUCTION CARE	FIELD TEST	INSTALLATION QUALITY VERIFICATION	FIELD TEST
Sand/Gravel Filter	* Material Properties:		* Placement Considerations	
	- Natural Water Content	ASTM D4959	- Soil water content if specified	ASTM D4959
	- Grain Size Distribution	ASTM D422	- Soil density if specified	ASTM D2922
	- Laboratory Hydraulic Conductivity	ASTM D2434	- Lift thickness	Visual
			- Verify compactive effort if density specified	Visual
	Post Construction: Natural filter must be protected from surface water sediments prior to burial			
Geotextile Filter	* Polymer Properties: Density, Denier, Polymer Type, UV Stability	Certification	* Placement Considerations	
			- Verify overlap of geotextile panels	Visual
	* Mechanical Properties:		- Verify no folds or wrinkles exist	Visual
	- Weight per square yard	Weigh	- Verify use of temporary anchorage if required	Visual
	- Tensile Strength (grab tensile)	ASTM 4632	- Verify sewn seams	Visual
	- Permittivity	ASTM D4491		
	- AOS	ASTM D4751		
	- Puncture Strength	ASTM D4833		
	Post Construction: Protect geotextile from surface water sediments and from wind or man caused movement			

The installation of the geotextile should be inspected to verify that panel overlap or sewn seams meet manufacturer's requirements. Additionally, any folds or wrinkles or damage to the panels must be eliminated and temporary restraint provided if necessary.

2.4 Erosion Control

Final cover systems on waste containment systems must be designed to limit the infiltration of surface water while at the same time require only limited maintenance for an extended period of time. Maintenance on such cover systems is significantly influenced by the degree of erosion that is allowed. For example, the EPA suggests that erosion be limited to less than 2 tons of soil per acre per year. The selection of a final cover system may also be influenced by the end use of the cover, e.g. park, or climatic conditions, e.g. lack of rain. Field inspection requirements for erosion control systems are presented on Table 2-4.

Vegetation and Topsoil

Surface vegetation may be the most economical erosion control system in those regions where rainfall exceeds evapo-transpiration. The vegetation will typically be a native grass tolerant of local climatic conditions. It should also limit spontaneous vegetation by non-desirable plants, germinate rapidly, and be compatible with the cap profile. Vegetation having exceptionally aggressive tap roots should be avoided.

Vegetation is usually bid on a cost per acre basis with a minimum weight of seed per acre specified. The seed placement cost should include required soil preparation (tilling, fertilizers, etc.), hydromulching, and any additional short-term erosion control required until the vegetation is established. Suppliers of fertilizer and seeds must certify that the fertilizer and seed meet project specifications. Placement of the seeds should be made in accordance with the supplier's instructions. The application rate, time of year, soil preparation, hydromulching, and watering schedule should be observed and documented.

Topsoil is used to support the growth of the vegetation on the cap and other locations that require vegetation. The topsoil is usually obtained on site from a stockpile cut from the construction area or from a nearby borrow area. Project specifications are typically vague regarding topsoil properties, but the organic content of the topsoil should be at least 3 to 5 percent, to support plant growth. Field monitoring is commonly limited to verification of the final layer thickness.

TABLE 2-4 EROSION CONTROL ELEMENT TESTING/INSPECTION

ELEMENT	MATERIAL PROPERTIES/POST-CONSTRUCTION CARE	FIELD TEST	INSTALLLATION QUALITY VERIFICATION	FIELD TEST
Vegetation	* General Properties: Seed Blend, % Weed, etc..	Certify	* Placement Considerations - Time of placement per specs - Soil preparation per specs or seed supplier - Hydromulching per specs or seed supplier - Watering schedule per specs or seed supplier	 Visual Visual Visual Visual
	Post Construction: Watering schedule must be maintained, protect from erosion and traffic prior to full growth.			
Topsoil	* General Properties: (if given in project specifications) - Natural Water Content - Grain Size Distribution - Soil PH - Organic Content, and - Nutrient Content	 ASTM D4959 ASTM D422 ASTM D4972 ASTM C311	* Placement Considerations - Lift Thickness - Water Content (if specified) - Density (if specified) - Surface Preparation (if specified)	 Visual ASTM D4959 ASTM D2922 Visual
	Post Construction: Protect from surface erosion prior to crop development			
Asphalt Cap	* Asphalt Mixture Properties - Percent Asphalt - Grain Size Distribution of Aggregate (if specified) - Compressive Strength Typically use certification by batch plant	 ASTM D915 ASTM D422 ASTM D1074	* Placement Considerations - Verify thickness of asphalt being placed - Verify weather is acceptable during placement - Density of asphalt (field test) - Ensure continuity of joints start of each day - Verify temperature of asphalt during placement	 Visual Visual ASTM 2950 Visual Visual
Concrete Cap	* Concrete Mixture Properties - Measure temperature of the mix - Determine how long truck has been on road - Slump test - Test for amount of entrained air in concrete - Make test cylinders for compression strength testing - Obtain batch ticket for each truck - Inspect Rebar	 ASTM C143 ASTM C231 ASTM C31 ASTM C39 Visual	* Placement Considerations - Observe placement to ensure that aggregate is not separated from fines in the concrete mix - Verify vibration of concrete to remove voids - Measure location of construction and expansion joints - Observe application rate of curing compound applied over fresh concrete surface	 Visual Visual Visual Visual
Rip-rap Cap	* General Properties - Rock Size Distribution	 ASTM D422	* Placement Considerations - Verify lift thickness - Check that geotextile is beneath rip-rap specified - Observe placement of stone to confirm maximum drop height and 'rolling' of stones	 Visual Visual Visual

Hardened Layers

Hardened covers provide an alternative to vegetative systems in arid regions that lack sufficient natural moisture. Additionally, hardened systems have been used to provide traffic and parking areas after closure of the waste containment facility. Asphalt and concrete hardened covers are normally limited to slopes less than 10 degrees.

Asphalt Cap --

An asphalt cap can be used to protect a capping system and provide a potentially usable area over a waste containment system (e.g. a parking lot). The asphalt cap can replace the vegetation, topsoil, drainage layer, and the biotic layer in the cap. In this application, the asphalt layer must provide the erosion resistance of the vegetation/topsoil, the lateral flow capacity of the drainage layer, and the protection of the biotic layer. The porous asphalt layer consists of an asphalt pavement system similar to that used in roadway construction. The asphalt supplier must certify that the materials meet the project specifications. Asphalt delivered to the site should be inspected for general compliance with these specifications. The temperature of the delivered asphalt mix should be measured and the batch ticket for each truck load should be filed for future reference.

During installation, the thickness, temperature, and density of the asphalt should be measured. Additionally, the weather must be monitored to avoid rain or cold temperatures that would hurt asphalt placement.

Concrete Cap--

Like asphalt, a concrete cap can protect a capping system and provide a potentially usable area over a waste containment system (e.g. a parking lot). The concrete cap replaces the vegetation, topsoil, drainage layer and the biotic layer in the cap. The concrete layer is similar to that used in roadway construction. Concrete suppliers must certify that the concrete meets project specifications.

The concrete delivered to the site should be inspected to determine how long the trucks have been on the road and if the concrete can be used. Material properties identified in the project specifications should be verified (see sample specifications in Table 2-4). The foundation below the concrete should be inspected for levelness, strength and the presence of water.

The concrete pour should be observed to verify that the aggregate is not separated from the fines in the concrete mix, and that the construction and expansion joints are properly located. The application rate of a curing compound over the concrete surface should be measured.

Rip-Rap Cap --

Rip-rap consists of natural stones ranging in size from approximately 1 inch to stones that weigh hundreds of pounds. Layers of these stones provide a significant impediment to wind and water related erosion. Rip-rap layers are commonly underlain with a geotextile filter to limit potential erosion of underlying fines. Field testing is typically limited to verifying that the delivered rip-rap meets project specifications for particle size.

The installation should be monitored to verify that thickness of the rip-rap layer meets project specifications. Placement of stone or rip-rap should be monitored to ensure that drop heights are limited. An underlying geotextile should be inspected for damage due to stone placement. When larger stones (>60 pounds) are placed over a geotextile fabric, drop height stone is commonly limited to 18 inches (45 cm). Alternately, a soil layer of 6 inches (15 cm) can be placed over the geotextile to provide a cushion and protect it from damage during rip-rap placement.

2.5 Protective Layers

Waste containment systems and covers frequently include layers that are intended to protect functional layers. Outer protective layers include the surface erosion control layers discussed above (section 2.4). This section discusses interior protective layers that function even after they are buried within the system. While some of the protective functions may be short-term or seasonal, e.g. a protective soil layer placed over a liner to protect it from freezing, most protective functions are long-term and are essential to the success of the waste containment system. Table 2-5 presents field tests that should be conducted to ensure material integrity and installation quality of protective layers.

Biotic Barrier

A Biotic barrier is used in the cap of a waste containment system to prevent small burrowing animals and plant roots from penetrating the drainage layer or the low permeability barrier. The biotic barrier usually consists of a 3 foot (1 m) thick layer of stone or cobbles. Vegetative intrusion can also be limited by herbicide impregnated geotextiles that provide time release protection. Field inspection is typically limited to verifying that the stone particle size and layer thickness meet project specifications.

TABLE 2-5 PROTECTIVE LAYER ELEMENT TESTING/INSPECTION

ELEMENT	MATERIAL PROPERTIES/POST CONSTRUCTION CARE	FIELD TEST	INSTALLATION QUALITY VERIFICATION	FIELD TEST
Biotic Barrier	* Mechanical Properties		* Placement Considerations	
	- Grain Size Distribution	ASTM D422	- Verify lift thickness	Visual
			- Verify specified soil/geotextile beneath ston	Visual
	Post Construction: Protect from stormwater sediments		- Observe placement of stone per specs	Visual
Geotextile	* Polymer Properties: Density, Denier	Certification	* Placement Considerations	
			- Verify overlap of adjacent rolls	Visual
	* Mechanical Properties: Per project specifications		- Eliminate fold or wrinkles during installation	Visual
	- Mass per Unit Area	Measure	- Provide temporary anchorage per specs.	Visual
	-Thickness			
	Post Construction: Protect from wind damage			
Soil Protective Layer	* Material Properties		* Placement Considerations	
	- Natural Water Content	ASTM D4959	- Water Content	ASTM D4959
	- Grain Size Distribution	ASTM D422	- In-place Density	ASTM D2922
			- Lift Thickness	Visual
	Post Construction: Protect layer from surface water erosion and dessication		- Visual Observation of Compaction Effort	Visual

Geotextile Protective Layer

A protective layer over the bottom liner, leachate detection layer and the primary leachate collection layer is required to protect these components from damage during construction and waste placement. The geotextile protective layer is normally a nonwoven material selected according to its unit weight (ounces/yard^2). The heavier the nonwoven material, the more cushion it provides. Suppliers of geotextile protective layer materials must certify that the geotextile meets the manufacturer's specifications.

The geotextile arrives on the site in rolls for installation. The material delivered to the site should be inspected for general compliance with project specifications and damage from shipping.

Soil Protective Layer

A soil protective layer over the liner, leachate detection layer and the primary leachate collection layer is required to protect these components from damage during waste placement and from the extremes in the weather. The soil should be selected for its resistance to erosion, strength, and stability on the side slopes of the waste containment system. Typically, an on-site soil can be used as the protective layer. The soil should be laboratory tested to verify that they meet the project specifications. Typical soil protective layer specification considerations are given in Table 2-5.

Special attention should be given to the installation of a soil protective layer over a geomembrane liner. Such installations require less rigorous compaction specifications for the first lift to avoid damaging the geomembrane during compaction.

2.6 Earthworks

Construction or closure of waste containment systems typically requires construction of earthen containment structures, such as dikes and berms, and the development of stable working benches (surfaces) over weak wastes or contaminated soils. Due to cost restrictions, earth work is usually done with either on-site or local soils. In view of the diverse nature of this material, close monitoring during construction is often necessary to achieve design conditions. Weak or soft spots in compacted soil are commonly detected by proof-rolling using a loaded dump truck. Any soil experiencing excessive rutting should be recompacted or excavated and replaced. Common field tests of earthwork are shown on Table 2-6.

TABLE 2-6 EARTHWORK ELEMENT TESTING/INSPECTION

ELEMENT	MATERIAL PROPERTIES/POST CONSTRUCTION CARE	FIELD TEST	INSTALLATION QUALITY VERIFICATION	FIELD TEST
Structural Fill	* Mechanical Properties - Natural Water Content - Grain Size Distribution - Moisture Density-Relationship - Atterburg Limits	 ASTM D4959 ASTM D422 ASTM D1557/698 ASTM D4318	* Placement Considerations - Soil water content as specified - Soil density as specified - Lift thickness verified	 ASTM D4959 ASTM D2922 Visual
	Post Construction: Protect layer from surface water erosion			
Soil Bedding Layer	* Mechanical Properties - Natural Water Content - Grain Size Distribution	 ASTM D4959 ASTM D422	* Placement Considerations - Soil water content as specified - Soil density as specified - Lift thickness verified - Verify final grade	 ASTM D4959 ASTM D2922 Visual Survey
Geotextile/Geogrid Bedding Layer	* Polymer Properties * Mechanical Properties - Weight per square yard - Strength - Wide-Width Strength	Certification Measure ASTM D4632 ASTM D4595	* Placement Considerations - Verify overlap of adjacent rolls - Eliminate fold or wrinkles during installation - Provide temporary anchorage if required	 Visual Visual Visual

Structural Fill

A structural fill is designed to support its own weight and that of any overlying systems without experiencing excessive deformation. Such fills are typically placed to develop a minimum shear strength or compressibility as assumed in design. Laboratory shear strength or compaction tests, made prior to construction, are used to establish acceptable moisture/density requirements for such fills.

Fill soils must be inspected at the site to ensure that they are suitable and have low plasticity (i.e., plasticity index <10) and no large stones (<6 inches). Compacted soils should be tested to verify that they achieve the minimum dry density established by the project specifications.

Soil Bedding Layer

A soil bedding layer is used to level the waste surface immediately below the cap. The bedding layer provides a smooth and stable working surface for the construction of the cap and is usually made from an on-site soil with good strength properties. Other than proof-rolling and measuring the final grade, little field testing is performed on bedding soils.

Geotextile or Geogrid Bedding Layer

A geotextile or geogrid bedding layer is used to level the waste surface and bridge any voids immediately below the cap. Additionally, the bedding layer provides a smooth and stable working surface for the construction of the cap. The geotextile or geogrid must have high tensile strength and be puncture resistant. Suppliers of geosynthetic bedding materials must certify that the materials supplied meet the manufacturer's specifications. The geosynthetics, which are delivered to the site in rolls, should be inspected to ensure general compliance with the project specifications and to check for damage.

The installation is usually monitored to confirm that geotextile or geogrid overlaps meet the manufacturer's specifications. Six (6) inch (15 cm) overlaps are common. Conformance testing of the geotextiles or geogrids can be performed as indicated in Table 2-6.

2.7 References

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SECTION 3.0

Field Sampling Strategies

Key elements of a waste containment system should be sampled and tested to verify that the materials meet project specifications and that they are being installed in accordance with the design drawings. Sample tests can also be used to monitor the construction process, predict trends in the quality of the installation, and detect sub-quality construction trends. A field sampling strategy in its simplest form can be implemented by "randomly" picking out a half dozen or so samples for testing, and accepting the area or lot if all the tests fall within the limits of the project specifications. A "lot" is a clearly defined production unit such as a given days batch of grout or a clearly identified production run of a geosynthetic product. While this may be an appropriate sampling plan in some cases, the risks associated with this plan should be known before implementing it. If factors such as sample size, sample location, and acceptance criteria are not correctly applied, the test results may not represent the quality of the area or lot being tested.

A sampling plan, whether it is implemented in the field or in a manufacturing plant, has several distinct parts:

1) Delineation of the sample area;

2) Determination of the number of samples by one of the following methods:
   a) Following the project specifications;
   b) Using the Sample Density Method, which specifies a minimum number of tests per unit length, area or volume;
   c) Using an Error of Sampling Method, such as ASTM E-122;
   d) Using Sequential Sampling;

3) Selection of the sample locations by one of the following methods:
   a) Include every potential sample location -- Census or one-hundred percent (100%) sampling of the area or lot;
   b) Select locations using the judgement of the project inspector -- Judgmental Sampling;
   c) Include every "nth" potential sample location starting with a randomly selected starting location corresponding to a randomly selected number less than "n". (For example, select every 10th location starting with the 9th location, ie. locations corresponding to 9, 19, 29, etc.) -- Fixed Increment Sampling;
   d) Selecting sample locations completely at random using a random number generator -- Strict Random Selection;
   e) Subdividing the test area into logical subareas and randomly selecting locations within each subarea -- Stratified Random Selection;

4) Obtaining and testing the samples using the appropriate methods;

5) Acceptance or rejection of the area or lot based on either:
   a) comparison of the sample statistics (mean, variance, etc. of the test values) with the limits presented in the project specifications;
   b) comparison of the sample statistics with pre-determined limits calculated to keep the construction process in control.

6) Development of a remedial action plan to change the construction process if the quality of the construction declines

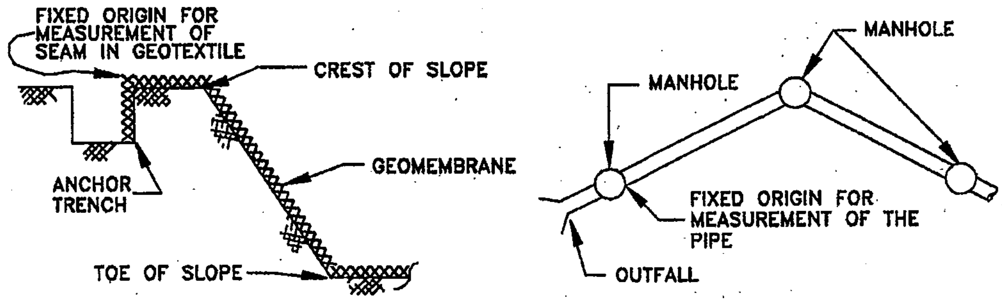
7) A clear method of historical documentation so that all of the original records, including the sample locations, test results, and the analysis of the test results (sample statistics), are available for project certification or future litigation.

3.1 Delineating the Area or Lot Being Tested

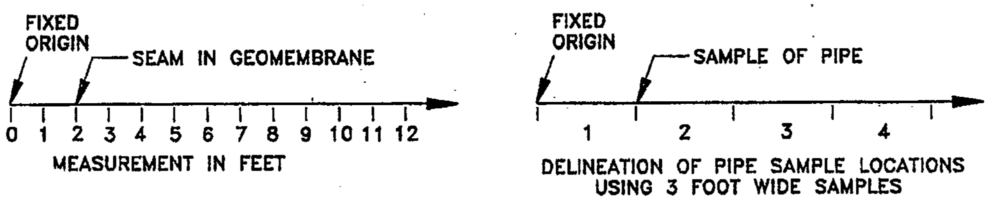
The area or lot being tested must be divided into potential test locations that can be clearly identified at a later time. The test area or lot should therefore be tied to an easily identified fixed reference point such as a manhole or the crest of a slope (see Figure 3-1a). Distance from the fixed location to the sample can be measured along a linear axis or using a pair of coordinate axes. For most sample selection schemes it is necessary that a numbering system be used to reference the potential sample locations or items. For example, samples from a geomembrane seam are referenced by measuring distance along the seam. Destructive testing of pipe, however may require samples of a specific length (e.g. 3.feet). The pipe can be marked off in 3-foot intervals with each segment given a number that identifies the sample (see Figure 3-1b). In delineating an area for sampling, a coordinate pair of axes must be used instead of a single axis. The sample locations can be delineated by distance measurements along both axes, or by assigning numbers to sample areas corresponding to subdivisions of an overall grid (see Figure 3-1c). Each sample should be marked or tagged to provide clear documentation of the test location.

3.2 Determining the Number of Sample Locations

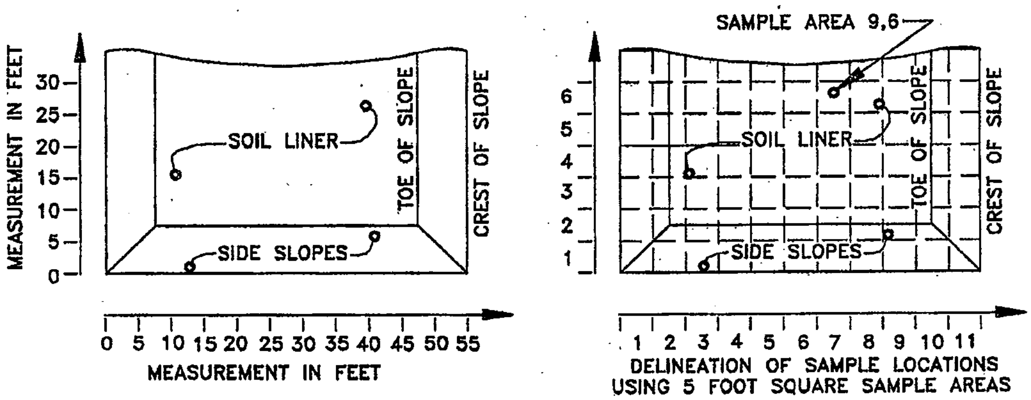
The number of sample locations required for testing a given element is normally included in the project specifications. Sometimes, specifications for sample locations determine the number of



3–1–a.) EXAMPLES OF FIXED ORIGINS



3–1–b.) EXAMPLES OF LINEAR SAMPLE MEASUREMENT



3–1–c.) EXAMPLES OF AREA SAMPLE MEASUREMENT

FIGURE 3-1 EXAMPLES OF DELINEATION AND MEASUREMENT OF LOT OR AREA BEING SAMPLED

samples, e.g. every 't' section of a seam in a flexible membrane liner must be tested. Apart from these instances, three methods -- sample density, error of sampling, sequential sampling -- are used to determine the number of samples to be tested.

<u>Sample Density Method</u>

The sample density method specifies the <u>minimum</u> number of sample locations per unit of measure (sample density) for a given element. This method is popular with regulatory agencies since it is readily applied and verified. It can be applied to linear systems (e.g. seams), surface areas (e.g. geomembranes), and volumes (e.g. grout). Table 3-1 shows typical sampling densities for all three of these element types. Note that sampling densities can be given in either area or volume units. For example, clay liner testing can be specified as number of tests/acre fill or number of tests/volume of fill. Common sampling densities for waste containment elements are presented in Appendix A.

<u>Error of Sampling Method</u>

The error of sampling method is used to determine the number of test samples required to represent the quality of the entire area or lot with an acceptable sampling error. The sampling error is defined as the maximum allowable difference between the sample estimate of lot or area quality and the measure of quality that would be determined by 100% sampling. Calculation of the number of tests needed to estimate the proportion of defective areas of a soil liner, using ASTM E-122, is shown in Figure 3-2.

The number of samples required by ASTM E-122 is a function of the importance of the element being tested (K), the allowable difference between actual and indicated quality (E), and an estimate of the actual number of defects in the area or lot (P). Calculations for a minimum number of tests for a clay liner are shown on Figure 3-2. Since a clay liner is a very critical element of a waste containment system, the K factor is 3. The allowable difference between the actual quality and the sample estimate of quality is set at 5 percent or P=0.05. An estimate of the actual number of defective tests in a given lot or area (P) requires some prior knowledge of similar applications which may require reviewing past records. This estimate can be adjusted as the project progresses to reflect actual site experience.

A minimum of 171 tests must be performed on the example clay liner to satisfy our assumed requirements. Note that ASTM E-122 does not incorporate the size of area or lot. In the case of a two foot thick clay liner, the test density (yd^3/test) is a function of the size of the liner as shown in Figure 3-2. Thus the 171 tests reflect approximately 1 test per 300 cubic yards of clay for a 15 acre site and 1 test per 500 cubic yards for a 25 acre site. Common sampling densities for clay liners range from 1 test per 250 to 500 cubic yards of clay (see Appendix A).

TABLE 3-1 EXAMPLES - SAMPLE DENSITY METHOD

ELEMENT/SYSTEM TYPE	PARAMETER	TEST METHOD	MINIMUM TESTING FREQUENCY*
Geomembrane/Linear	DT Seam Test	ASTMD413 ASTMD3083	1/500 Ft. Seam
Clay Liner/Area	Density	ASTMD2922 or ASTMD2937	5/acre/6" lift
Clay Liner/Volume	Density	ASTMD2922 or ASTMD2937	1/500 YD^3
Grout/Volume	Slump	ASTMC143	1/500 YD^3

* For landfill liners - the minimum testing frequency may be decreased (e.g. 1/1000 ft of seam) for caps or temporary applications as required.

REFERENCE: ASTM E–122 ERROR OF SAMPLING METHOD

DEFINE NUMBER OF TESTS (n)

$$n = (K/E)^2 P(1-P)$$

WHERE P = ESTIMATE OF THE FRACTION OF DEFECTIVE TESTS PER UNIT

E = MAXIMUM ALLOWABLE DIFFERENCE BETWEEN THE ESTIMATES OF QUALITY FROM n SAMPLES AND 100% TESTING

K = A FACTOR CORRESPONDING TO THE PROBABILITY THAT THE SAMPLING ERROR WILL EXCEED E. (SEE TABLE)

TABLE – k FACTOR

K	PROBABILITY OF ERROR EXCEEDING E	IMPORTANTCE OF ELEMENT
3	0.003 (3 in 1000)	VERY CRITICAL
2.58	0.01 (10 in 1000)	CRITICAL
2	0.045 (45 in 1000)	
1.96	0.05 (5 in 100)	
1.64	0.10 (10 in 100)	NOT CRITICAL

EXAMPLE APPLICATION

DEFINE NUMBER OF MOISTURE/DENSITY TESTS FOR SOIL LINER

ASSUMPTIONS:

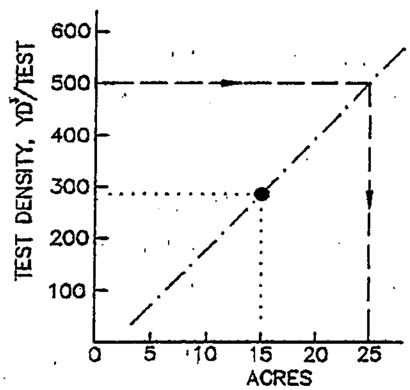
P = 5% ⟹ 5 OUT OF 100 TESTS ARE DEFECTIVE

E = 5% ⟹ ALLOWABLE DIFFERENCE = ±5%

K = 3 ⟹ VERY CRITICAL ELEMENT

$$n = (3/0.05)^2 0.05\,(1-0.05) = 171 \text{ TESTS}$$

NOTE: ACTUAL TEST DENSITY IS A FUNCTION OF VOLUME OF SOIL LINER, e.g. 15 ACRE SITE WITH 2 ft. LINER



TEST DENSITY = 48642 YD³/171 = 248 YD³/TEST

FIGURE 3-2 NUMBER OF SAMPLES-ERROR OF SAMPLING METHOD

Sequential Sampling

The Sequential Sampling scheme is designed to minimize the required sample number when the quality of the area or lot is either exceptionally good or very poor. Most sampling plans require a fixed sample size (determined prior to construction) which is independent of the results observed at the first sample locations. Sequential sampling uses the results of the tests as they are conducted to adjust the number of samples required and the acceptance criteria. Areas or lots with high or low quality require a smaller number of tests than those with marginal quality. Note that the sequential sampling method defines both the number of samples and the acceptance criteria which depend on the results of earlier sample test results.

A sequential sampling plan requires that after each sample location, or small group of locations, is evaluated that one of three decisions is made about the test area or lot from which the sample(s) was(were) taken:

- The test area is accepted
- The test area is rejected
- The evidence is not sufficient to make a decision without an unacceptable risk of error

These three decisions are illustrated by the three regions on the chart shown on Figure 3-3. If the last decision is made, more sample locations must be selected and evaluated. This process is continued until the test area is accepted or rejected or a limit on the number of test is reached e.g. all. Typically a graph as shown in Figure 3-3 is used to implement this sampling scheme.

Four variables must be determined to implement this sampling plan. These variables include:

P_1 = acceptable proportion of defective sample locations in a test area;

P_2 = unacceptable proportion of defective sample locations in a test area;

δ = the probability of rejecting an acceptable test area. (the quality of the test area is acceptable but the sample results indicate that it is unacceptable);

ß = the probability of accepting an unacceptable test area. (the quality of the test area is unacceptable but the sample results indicate that it is acceptable).

These values, which are selected by the person designing the sampling plan, should reflect the desired precision of the test results, the importance of the tested element and the cost and delays due to sampling and testing. The consequences of a wrong decision are key

REFERENCES (6,7,8)

DEFINE ACCEPTANCE CRITERIA

P_1 = % DEFECTS ACCEPTABLE

P_2 = % DEFECTS UNACCEPTABLE

δ = % PROBABILITY OF REJECTING A TEST AREA WITH QUALITY GREATER THAN P_1

β = % PROBABILITY OF ACCEPTING A TEST AREA WITH QUALITY LESS THAN P_2

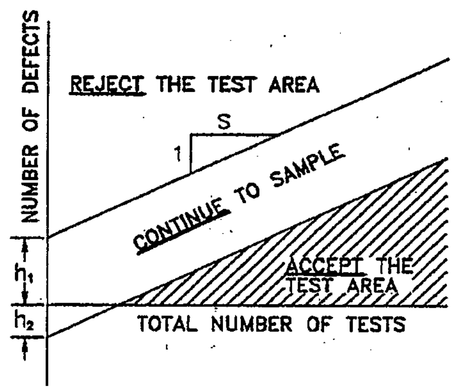
DEFINE ACCEPTANCE/REJECTION CHART

$$A = \log((P_2/P_1)*((100-P_1)/(100-P_2)))$$

$$h_1 = \log((100-\delta)/\beta)/A$$

$$h_2 = \log((100-\beta)/\delta)/A$$

$$S = \log((100-P_1)/(100-P_2))/A = \text{SLOPE}$$



EXAMPLE APPLICATION

DEFINE ACCEPTANCE CRITICAL FOR DRY DENSITY OF STRUCTURAL FILL.

ASSUMPTIONS:

$P_1=5$ $P_2=10$ $\delta=10$ $\beta=20$

$A = \log((10/5)*((100-5))/(100-10))) = 0.32$

$h_1 = \log((100-10)/20)/A = 2.04$

$h_2 = \log((100-20)/10)/A = 2.82$

$S = \log((100-5)/(100-10))/A = 0.07$

$\therefore$ MINIMUM OF 40 TESTS

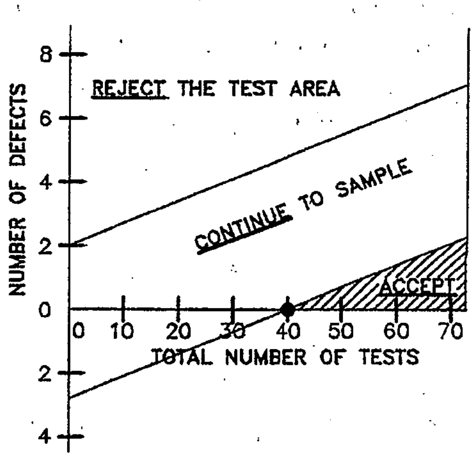


FIGURE 3-3 NUMBER OF SAMPLES-SEQUENTIAL SAMPLING

consideration when selecting these values or limits. If the constraints are too rigid, the required sample size (number) will be so large that the associated costs are prohibitive. Hence it is necessary to tradeoff up-front costs for sampling, the costs of redoing a lot rejected in error (the sample gave misleading results indicating a good lot was defective), and the costs of failing to detect a faulty lot until much time has passed. If the cost of rejecting good material is high then δ should be small. If on the other hand acceptance of inferior material is high, the typical situation for environmental materials, then ß should be small.

An application of sequential sampling acceptance criteria to structural fill is given in Figure 3-3. Structural fill is an element that, while important, is less critical to the success of a waste containment system than such elements as clay or geomembrane barriers. Hence in this situation the decision maker may be willing to tolerate more defects (larger P_1 and P_2) and be less concerned about incorrect decisions (larger δ and ß). If so, the number of required samples will be less than for materials which are more critical to the success of a fill. The importance of an element is reflected in the selection of the four variables required to define the acceptance chart.

Example (Figure 3-3)

The percent defects in an unacceptable fill (P_2) is assumed to be 10%. This is twice as tolerant as the criteria used in the previous example for clay liner material. The percent defects in an acceptable area (P_1) was selected as the mean of the acceptance range (<10%). Percent probabilities for accepting a defective test area (ß) or rejecting an acceptable test area (δ) are selected in the example to reflect the lower importance of the structural fill. For a critical element, ß will be smaller and δ could be larger since it is more important that a defective critical element not be accepted.

A minimum of 40 density tests must be performed to get acceptance of the structural fill using the sequential sampling chart developed above. If no defective density tests occur in these forty (40) tests, then the structural fill is accepted. If two (2) or more defective locations are found the lot is rejected. If one (1) defective location is found then additional sample locations must be selected and evaluated. Testing must continue until the chart indicates that the lot is acceptable or must be rejected.

3.3 Selection of Sample Locations

Field sampling strategies for selecting a single sample location may follow several sample location criteria. This is particularly true for critical elements such as the seams of geomembrane liners. The protocol for locating test samples on seams includes all of the following criteria:

For Non-Destructive Testing
- 100% Testing

For Destructive Testing
- 1 per 500 Feet (Incremental)
- Judgmental
- Minimum 1 per seam (Stratified)

Thus the sample location strategies presented in this section may be combined for a given element.

100% Sampling

In theory, determining the true quality of a product would require sampling the entire product -- which is known as 100 percent sampling. Although non-destructive testing methods can be used to sample and test all of the product or test area, this requires a significant investment of time and capital. For these reasons, a 100% sampling plan is used only to test the most critical elements in waste containment structures; the seams in the synthetic liners used in landfills, waste piles and waste ponds. Because a defect in the seam will allow a release of waste, 100% testing is considered necessary.

Since a 100% sampling plan is rigorous, the sampling and testing program should be designed to minimize inspector fatigue. A sufficient number of testing crew breaks and shift changes should be used to avoid errors in the sampling and testing program.

The 100% Sampling Plan:

Step 1 Develop a means of delineation and measurement that can be used to determine the sample locations over the entire test area. Since this a 100% sampling plan, the delineation will not be used for sample selection but will serve to ensure that all locations are tested and to locate any defective locations.

Step 2 Test the entire area or lot using a non-destructive test method (see Appendix A). Careful documentation must be made of the starting and stopping locations, material batch numbers, installation crews, and other variables that may affect the testing results. Compare the results of testing to the project specifications. All areas that do not meet the project specifications will be rejected and removed or repaired (and re-tested).

Example -- Installation of a 60-mil HPDE geomembrane liner. The 100% Sampling Plan would be implemented as follows:

Step 1 Develop a geomembrane panel and seam identification plan similar to that shown on Figure 3-4. This is commonly based on the panel installation drawing provided by the liner installer.

Step 2 Test all seams using the vacuum box test for extruded seams or the pressurized air channel test (GRI-GM6) for double hot wedge seams (see Reference 3-9). Locations of seam defects are identified by both their seam number and distance from a given end of the seam, e.g. north or west ends being zero. All test failures and observed visual defects are entered into a repair log similar to Figure 3-5.

Note that repair logs such as presented in Figure 3-5 may include observations of problems that may not be considered failure based on vacuum box or pressurized air channel tests. This includes data related to seam preparation such as the cleanliness of the seam, excessive grinding (both depth and breadth), and panel preparations. Such observations may be based on the inspector's judgement, discussed in the next section, and serve as an appropriate supplement for critical installations.

Judgmental Sampling

Judgmental sampling relies on the experience and judgement of a facility inspector to select the location and/or number of samples to be tested. The inspector may attempt to approximate random selection in his location choices or he/she may deliberately select areas that have been subject to failures in the past -- i.e., worst case locations. Sometimes a combination of approaches may be appropriate to establish mean values and outer test value limits (see below). The results of this subjective sampling approach may be biased. The major deficiency of this approach is that there is no way to statistically test for bias or to derive statistical estimates of the properties of the sampled area. Statistical principles are based on the assumption that potential sample units ("locations" in the context of this discussion) have a known probability of being included in a sample.

Although judgmental sampling is not suitable for a large sampling program, it may be useful and even necessary in some cases. For example, when testing a very small area or lot, a judgmental approach may provide better estimates of area or lot quality than other selection methods. Additionally, if the testing procedure is very expensive, it may not be feasible to test enough sample locations to predict with acceptable confidence the quality of an area or lot. A judgmental sampling plan can select a "worst case" location to provide an estimated best or worst case limit for the test area. Such worst case sampling applications include looking for excessively wet soil, excessive sump in grout, and others given in Appendix A.

PANEL AND SEAM IDENTIFICATION PLAN

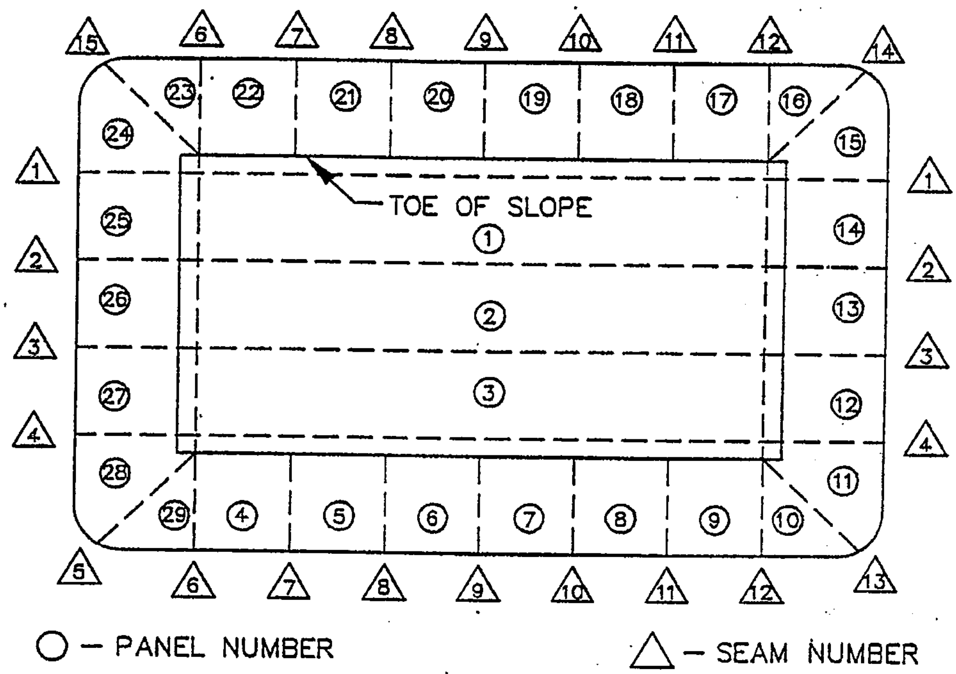


Figure 3-4 Panel and Seam Identification Plan

GEOMEMBRANE REPAIR LOG

Date	Seam	Panels	Location	Material Type	Description of Damage	Type of Repair	Repair Test Type	Tested By

Figure 3-5 Geomembrane Seam Repair Log

A Judgmental Sampling Plan:

Step 1 Delineate the sample locations over the entire test area.

Step 2 Determine the number of samples required for the test area. One of the following methods are usually used:

a. The inspector uses his judgment to select the number of samples.
b. A minimum sample density is typically required in the project specifications. For example, the project specifications may specify that a field test be made every 2000 square feet of soil placed in each lift.

Step 3 Use judgment to select the test locations in each lift.

Step 4 Sample and test the selected locations.

Step 5 Compare the testing results with the project specifications. All areas that do not meet the project specifications will be rejected and removed or repaired (and re-tested).

Fixed Increment Sampling

The fixed increment sampling method uses a randomly selected starting location and a fixed interval between each consecutive sampling location. This method is straight forward and easy to implement in the field. However, the inspector must ensure that the sampling interval does not skip over critical parts of the installation. For example, in the destructive sampling of geomembrane seams, the fixed increment should not be so large that all side slopes are missed. In situations like this it is normally better to use multiple independent sampling schemes. Areas with less potential problems could be represented by a relatively small number of sample locations, whereas critical areas could be represented by a relatively large number of sample locations. Typically the actual sample size is larger for large areas (non critical areas) than for small areas (critical areas), but the sampling frequency (proportion of potential locations that are sampled) for the former will be less than for the latter. The same type of sampling plan (fixed increment, randomly selected, 100 percent sampling, etc.) or different plans can be used for the different types (non critical and critical) of areas. For example fixed increment sampling could be used for the bottom seams and random sampling for the side slope seams.

To implement a fixed increment sampling plan to represent an area, or material, the area must be separated into equally sized sampling locations that can be uniquely identified. One approach is to overlay the area with a rectangular grid and number the grid sections sequentially using a serpentine approach. Sample locations are selected from the columns of the grid starting at the top of the first column and continuing to the top of each successive column. The process is similar to reading the columns of a newspaper; an article is read by starting at the top of the first column and proceeding to the bottom before moving to the top of the next column. Two dimensional coordinates could be used as an alternative.

If the starting location for the fixed sampling scheme is randomly selected, traditional sample statistics (means, variances, etc.) are commonly used to estimate the quality of the sampled area(s). If the starting location is selected by judgement, calculation of sample statistics to estimate properties of the sampled area is questionable.

A Fixed Increment Sampling Plan:

Step 1 Delineate the sample locations over the entire test area.

Step 2 Determine the number of samples and tests required using either the error of sampling method or the sample density method.

Step 3 Select a starting point either by judgment or by a random selection process.

Step 4 If the sample density method is used, then a test sample must be taken for each unit of measure that is made from the starting point. For example if 1 sample is to be selected every 200 feet, then the unit of measure is 200. Hence the first sample location is selected from the first 200 feet and 1 sample location is selected from each successive 200 feet of material. If the number of samples is determined using error of sampling, the interval is determined by dividing the total size of test area by the number of samples plus one. For example, if a seam in a geomembrane is 1000 feet long and the number of tests required is calculated as 4, the interval will be 200 feet (1000 ÷ 5). The starting point "n" should be randomly selected inside the first interval (200 feet) and the remaining samples selected at 200 feet intervals, ie. "n"+200, "n"+400, ---.

Step 5 Compare the test results to the project specifications. All areas that do not meet the project specifications will be rejected and removed or repaired (and re-tested).

Random Sample Selection

In order to use sample statistics to estimate area characteristics, test locations should be randomly selected. Random sampling requires that every potential sample location must have a known probability (typically equal for all locations) of selection. Situations where an inspector looks over an area and selects test locations can not be accurately described as "random" selection. Two typical methods of random sample selection that are applicable to waste containment system quality control and quality assurance are simple random sampling and stratified random sampling. The total number of required samples is based on a consideration of the maximum acceptable error rate and the level of acceptable risks for rejecting good material and accepting bad material. The procedures for determining sample size follow those described in sections entitled "error of sampling" and "sample density method."

Simple Random Sampling -- All potential test locations of the area, or lot, being evaluated have an known (usually equal) chance of being selected under a simple random sampling plan. Typically an area is divided into equal sized locations which are assigned unique number identifiers. Random numbers are used to select identifiers and hence locations for testing. The source of random numbers is a random number generator, which is available on most computers, or a random number table. If a random number table such as Table 3-2 is used, select the first number less than, or equal to, the total number of potential sample locations by closing your eyes and pointing to any point on the Table. If the number which is pointed to is larger than the total number of locations take the next number (below, next to, or above) that is less than or equal to the total number of locations. Record the initially selected number and the series of numbers less than or equal to the total number of locations directly above or below this number. Once the bottom of the column is reached, the next number can be selected at the top of the next column. If numbers are repeated, select additional numbers from the Table. Continue selection of numbers until the required number of sample locations are identified. Once the numbers are selected, the last number in the series should be marked and becomes the starting point for selecting additional samples, if needed.

The Error of Sampling Method is used to determine the appropriate number of test locations to be included in the simple random sample.

Table 3-2 Portion of Random Number Table

83	8	74	15	10	84	10	26	61	57	72	17	84
74	16	73	7	10	78	53	22	46	63	31	98	76
12	27	20	1	20	26	22	47	58	46	31	7	34
6	74	46	74	30	42	97	56	19	62	6	85	43
30	47	33	54	2	15	83	83	6	18	7	86	81
25	1	3	89	34	46	27	29	4	69	89	33	29
90	96	52	84	53	18	91	10	75	16	95	62	52
27	71	5	13	73	7	38	29	95	40	91	44	55
12	64	37	64	95	69	85	87	98	34	30	7	70
77	54	98	19	2	24	50	34	50	71	93	60	30
2	72	7	63	96	34	80	15	6	35	61	11	36
83	78	43	83	94	54	14	20	74	65	35	74	80
57	43	30	48	17	70	22	84	84	10	89	34	98
28	19	64	21	93	70	28	42	22	0	74	71	38
32	26	96	79	16	19	34	48	77	26	54	17	5
93	46	41	23	21	75	25	89	43	27	82	68	56
54	94	58	51	14	84	71	32	52	25	16	72	13
42	72	7	42	42	96	52	78	22	57	57	27	58
63	26	90	89	80	9	57	27	42	67	83	77	37
64	36	1	53	74	41	88	76	14	56	47	92	91
71	87	42	31	50	35	2	68	15	87	8	26	99
78	53	60	49	65	51	87	35	39	44	27	86	15
18	16	98	47	2	96	3	81	89	21	73	89	28
54	98	87	89	22	39	52	29	73	34	77	19	57
45	25	35	25	76	56	0	43	92	44	55	77	83
69	69	40	87	64	63	41	72	95	29	46	67	66
67	98	10	96	6	83	87	70	37	47	17	85	63
59	98	17	80	45	42	47	86	26	41	91	87	16

Notes: 1. Range of random numbers is 1 to 100.
2. 00 in table equals 100.
3. The shaded number is starting point in the example.
4. Table of random numbers generated on personal computer.

Table 3-3 shows a case in which five (5) sample locations are to be selected out of a total of 25 possible locations. Since numbers greater than 25 will not correspond to an existing location, the random numbers chosen from Table 3-2 that are greater than 25 are discarded. The sample locations chosen in this example are 25, 10, 20, 2, and 17.

Stratified Random Sampling -- Some elements of a waste containment system, such as soil lifts in a clay liner, have a clear repetitive organization. In these cases, it may be advantageous to take a random sample of locations from each of the repetitive units -- this is known as stratified random sampling. That is, the lot of items are divided into sublots (or strata) and an independent random sample of locations are selected from each sublot. In some situations certain subareas of a larger area may be particularly critical to the overall performance of a site. For example side seams may be more likely to leak than those in the bottom. In these situations it is very appropriate to sample a larger proportion of side seam locations than bottom seam locations. Within each sub area a simple random sample of test locations is randomly sampled. The other use of stratified sampling is to insure that no subarea of a site is missed by an evaluation program. While a random sample of a large area may miss some subarea (stratum), a stratified random sampling plan is guaranteed to test each one.

A Random Sampling Plan:

The procedure below follows a strict random sampling plan. If a stratified random sampling plan is used, this procedure is applied to each stratum. The number of samples taken from each stratum is based on the anticipated variability of the test results within each stratum, desired overall precision of test results, etc. A survey sampling reference or knowledgeable statistician should be consulted to learn more about the weighing procedures used to calculate strata sample sizes, computer overall sample statistics, etc.

Step 1 Delineate potential sample locations over the entire test area (See Section 3.1).

Step 2 Determine the number of samples using either the error of sampling method or the density test method.

Step 3 Select sample locations at random using a random number table or a random number generator.

Step 4 Collect test material from the randomly selected locations and perform the required tests.

Step 5 Compare the test results to the project specifications. Any areas that do not meet the project specifications will be rejected and removed or repaired (and retested).

TABLE 3-3 EXAMPLE OF RANDOM SAMPLE SELECTION OF 5 LOCATIONS FROM AN AREA CONSISTING OF 25 LOCATIONS

Item No.	Random No.	Disposition
1	31	discard(>25)
2	49	discard(>25)
3	47	discard(>25)
4	89	discard(>25)
5	25	*select*
6	87	discard(>25)
7	96	discard(>25)
8	80	discard(>25)
9	10	*select*
10	10	discard(duplicate)
11	20	*select*
12	30	discard(>25)
13	2	*select*
14	34	delete(>25)
15	53	discard(>25)
16	73	discard(>25)
17	95	discard(>25)
18	2	discard(duplicate)
19	96	discard(>25)
20	94	discard(>25)
21	17	*select*

3.4 Acceptance/Rejection Criteria

With the exception of the sequential sampling method discussed in Section 3.2, at this point no criteria for acceptance or rejection of a lot or area has been established. Sampling frequency, sample locations, and acceptance/rejection for <u>individual</u> tests have been discussed. This section deals with criteria for accepting or rejecting a lot or area (e.g. a given lift of fill on the basis of a test series).

<u>No Defects Criteria</u>

The no defects criteria is straightforward. If any test value falls outside the limits in the project specifications, that area will be rejected and either replaced or repaired and then re-tested. This criteria is typically applied to the 100% and judgmental sampling methods.

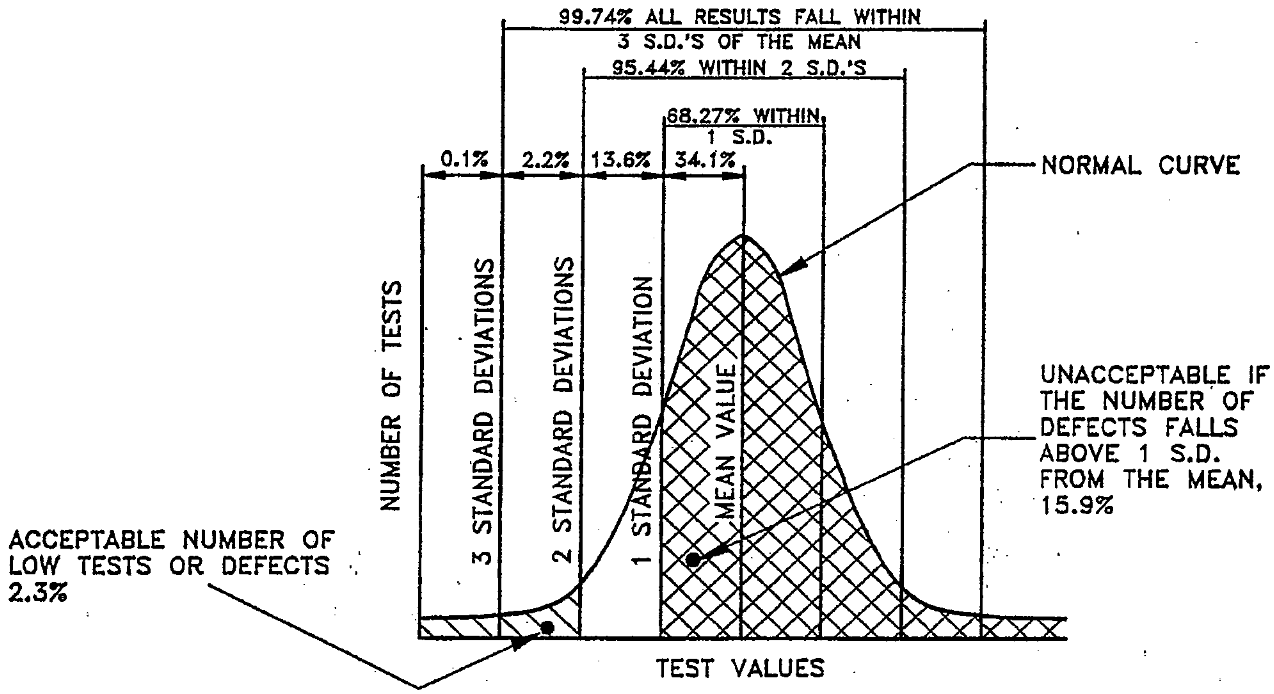
<u>Statistical Value Criteria</u>

Comparison of the sample statistics such as the mean, range, standard deviation, and variance, to those specified in the project specifications can be used to accept or reject the area being tested. Statistical value criteria assumes that sample test statistics will follow a known probability distribution; most people are familiar with the normal distribution curve as shown in Figure 3-6. This assumed distribution of sample statistics is used to establish an upper limit on the number or proportion of defective tests that can be accepted in a sample of location test results. It has been shown that the means of samples containing at least 30 items (locations in the context of this presentation) are usually normally distributed. As shown on the above figure of the normal distribution, if the acceptance range is defined as the mean ± one standard deviation, then 15.9% of the sample test results will be below and 15.9% above the criteria (total defective samples are 31.8%). Expanding the acceptance criteria to mean ± two standard deviations reduces the proportion of sample locations that fall outside the acceptable range to 4.6% (2.3% above and 2.3% below criteria). Acceptance criteria can be selected to reflect the critical nature of the element being tested. While not as easily applied as the no defect method, the statistical criteria method recognizes that the quality of some installations and materials is not impacted significantly when individual test samples fall outside specified limits. An example of this can be seen in the concrete industry in the acceptance of concrete at construction sites (5). Here the <u>average</u> compressive strength of the concrete tests must be greater than a minimum code value that is a function of the design strength and the standard deviation of the field tests.

In some cases project specifications provide statistical limits. For example they might specify that the mean permeability of ten soil samples shall not be less than 10.5E-7. Typically, project specifications only provide acceptance limits. For example the soil permeability shall not exceed 10E-7. Many times these acceptance limits can be used to estimate upper or lower cut-off values for the sample statistic of concern (mean, variance, etc.); if the sample statistic (mean, variance, etc.) is above or below the estimated cut-off values, the test area is rejected.

The following illustrates an approach for estimating the lower cut-off value for the sample mean of a particular test measurement based on lower acceptance limits:

Step 1 Determine from (project specifications) the <u>minimum and/or maximum value</u> of the test results considered acceptable.



NOTE: ACCEPTABLE AND UNACCEPTABLE VALUES ARE ILLUSTRATIVE OF THE EXAMPLE IN THE TEXT. DIFFERENT VALUES MAY REQUIRE FOR DIFFERENT APPLICATIONS.

Figure 3-6 Normal Distribution of Data

Step 2 Determine the importance of the characteristic being tested to the function of the whole system (liner or other component). Table 3-5 can be used to relate relative importance to the acceptable percentage of test results that are below or above the acceptable levels.. An element is considered very critical to the function of the whole system if its failure creates a failure of the whole system. For example, failure in the seams of a geomembrane liner in a waste containment system can not be tolerated. Conversely, a soil liner that is constructed in several individual lifts can tolerate some below specification test values because multiple layers are applied.

Step 3 Calculate sample statistics. The mean and standard deviation are calculated using the following formulae:

Mean: $\overline{x} = (1/n)*\sum x_i$ (3-2)

Standard Deviation: $s = sqrt[(1/(n-1)*\sum (x_i-\overline{x})^2]$ (3-3)

where $\overline{x}$ = the sample mean,
n = the number of sample locations
x_i = the individual sample test result
i = the number of the sample
s = sample standard deviation

Step 4 Compute statistical cut-off values. Assuming the test statistic of concern (mean) is normally distributed (distribution of means follows a bell shaped curve) use Table 3-5 to select the maximum percentage of locations that can be tolerated with test results that are less than the acceptance limits. This percentage should then be used in Table 3-6 to select the lower statistical cut-off value for the sample mean; this value is the minimum acceptable sample mean that will ensure that the percentage of locations with measurements less than the lower acceptable limit (as required in the project specifications) is not greater than desired.

If the <u>sample mean</u> of the test data falls below the calculated lower statistical cut-off value, the area being tested is rejected. It must be replaced or repaired and then re-tested.

TABLE 3-5 RECOMMENDED PERCENTAGE OF LOW TEST RESULTS

Importance of the Element to the Function of the Whole System	Recommended Percentage of Low Test Results (Probability)
Values below the lower limit can not be tolerated	0.13 (1.3 in 1000)
Element is critical to the function of the system	1.1 (11 in 1000)
Element is not critical to the function of the system	10.1 (1 in 10)

TABLE 3-6 LOWER STATISTICAL CUT-OFF VALUE FOR THE SAMPLE MEAN

Minimum Sample Mean	Percentage of Measurements Less than the Lower Limit
LL + 0.00s	50.0
LL + 0.10s	46.0
LL + 0.20s	42.1
LL + 0.30s	38.2
LL + 0.40s	34.5
LL + 0.50s	30.9
LL + 0.60s	27.4
LL + 0.70s	24.2
LL + 0.80s	21.2
LL + 0.90s	18.2
LL + 1.00s	15.9
LL + 1.10s	13.6
LL + 1.20s	11.5
LL + 1.28s	10.0 *
LL + 1.30s	9.7
LL + 1.40s	8.1
LL + 1.50s	6.7
LL + 1.60s	5.5
LL + 1.70s	4.5
LL + 1.80s	3.6
LL + 1.90s	2.9
LL + 2.00s	2.3
LL + 2.10s	1.8
LL + 2.20s	1.4
LL + 2.30s	1.1 *
LL + 2.40s	0.8
LL + 2.50s	0.6
LL + 2.60s	0.45
LL + 2.70s	0.35
LL + 2.80s	0.25
LL + 2.90s	0.19
LL + 3.00s	0.13 *

LL = lower acceptance limit of the test values as specified in the project specifications

s = sample standard deviation

Example - Determine and apply the statistical limit approach to the soil liner data given in Table 3-7. This data was obtained from a clay liner constructed in five lifts with 20 density tests performed per lift. Project specifications require a minimum density of 92 PCF (1.47 t/m^3).

From Table 3-5, the recommended percentage of low test results is given as 1.1. This leads to a required mean value (see Table 3-6) of 92 PCF plus 2.3 standard deviations. For the data on Table 3-7, the mean of the sample soil density measurements must exceed the statistical cut-off value of 115 PCF (1.84 t/m^3). The sample means for the individual lifts range from 102.1 to 106.6 so that all fail. Likewise since the overall sample mean is 104.1 the liner as a whole also fails. The installed liner is therefore not acceptable based on this criteria.

Maximum Number of Defects Criteria

Project specifications may set a fixed number of allowable defects. A defect is considered a test value that falls outside the limits set in the project specifications. The maximum number of defects criteria is straightforward in its application. No area will be accepted if the number of the test results that fall outside of the testing limits is larger than the specified number. If the maximum number is exceeded, the area will be rejected and either replaced or repaired and re-tested. A common example of this criteria occurs in the destructive testing of geomembrane seams. At each test location, five peel and shear (see Appendix A) tests will be performed on coupons obtained from the seam. Typical project specifications will allow for a maximum of 1 coupon test failure for peel or shear. This method is similar to the statistical limit criteria insofar as a maximum number of defects are defined. The difference is that this method simply specifies a fixed number of defects while the statistical limit criteria method uses a number that is derived from the standard deviation of the data.

Assignable Variable Monitoring (Control Charts)

The above sample acceptance methods are not used to determine the source of test failures. The failure of a given test may be the result of random or assigned variations. While random variations cannot be predicted statistically, assignable variations are those that can be statistically traced to a specific field activity or material. For example, assignable variations related to the seaming of geomembranes may include different seaming crews, daily temperature variations, fatigue of seaming crews (related to time of testing or temperature), specific welding machines, etc. Assignable variable monitoring provides a means of distinguishing assigned variation in test results from random variations. This allows the relative quality of the element produced by all field crews, machines, etc. to be compared. This method is used to monitor data from one of the previously discussed statistically-based sampling plans. It allows the CQA manager to either increase the frequency of testing during periods of excessive failures or to identify those variables common to the sample groups experiencing excessive problems.

A graphical approach to explore the assignable variable monitoring method begins by plotting a 'control chart' for the assigned variables being monitored. The basic tabular procedure for making a control chart is shown on Table 3-7. Note that control charts can be constructed after all testing is completed or can be maintained during the actual testing. The latter provides the greatest opportunity to detect. Fortunately, this process is very easily adapted to spread sheets commonly available on personal computers. The graphics approach provides valuable clues about assignable variability. To test whether the observed trends are the result

TABLE 3-7 STATISTICAL DATA - SOIL LINER DRY DENSITIES
- Soil Liner - 5 Lifts, 20 Tests/Lift (1 per 250 cy)

Clay Liner - Field Dry Densities (pcf)					
Sample no.	Lift 1	Lift 2	Lift 3	Lift 4	Lift 5
1	112	109	106	103	100
2	96	96	106	100	93
3	93	93	100	93	100
4	100	103	103	100	109
5	100	106	115	115	109
6	103	106	96	103	103
7	72	103	112	100	96
8	134	103	112	109	112
9	112	112	109	75	96
10	106	109	112	126	121
11	112	118	109	106	118
12	112	116	121	118	109
13	112	121	103	82	109
14	93	109	112	109	114
15	87	114	97	106	106
16	103	99	97	103	109
17	84	87	103	103	103
18	109	92	87	92	109
19	102	111	89	96	114
20	106	98	103	103	101
MEAN	102.4	105	104.6	102.1	106.6
STD. DEV.	13.1	9.2	8.6	11.4	7.5
RANGE	62	34	34	51	28

Total Mean = 104.1 Total Std. Dev. 10.0 Total Range = 62

Minimum Dry Density (Specs) = 92 pcf ________ = Day Breaks

1 pcf = .0128 kg/cubic meter

of random fluctuations in data or can be attributed to specific causes requires more rigorous statistical techniques such as analysis of variance. Numerous books are available to aid in designing studies to test for assignable variability. The other alternative is to consult with a knowledgeable statistician.

Identification of Outliers -- The control chart calculated using Table 3.7 defines all data within 3 standard deviations of the mean. This means that 99.74% of statistically meaningful data should be within these bounds. Data points that are outside of the control chart bounds are considered outliers. Such outliers are assumed to be caused by assigned or random variations. Other more rigorous techniques for outlier detection are described in various several statistical text books.

A table of daily test pass/fail data is provided on Figure 3-7 to illustrate the use of a control chart to identify outliers. The tabulated control chart for this data is plotted as shown on Figure 3-8. This plotted control chart displays the running portion of failed tests along with the upper control limits (UCL). The plot shown gives the ratio of failed seam tests to total seam tests and therefore does not use a lower control limit, since no failure is the goal. Both the upper control limit and control chart can be calculated for the total sample of locations or as moving statistics of sub-samples. Statistics can be calculated for each day's measurements and plotted. Note that the moving test statistics can miss outliers based on the final available data base.

Obviously the focus in quality assurance is minimizing the cases where the UCL is exceeded. A detailed evaluation of the assigned variables (e.g. seaming crews, cold vs. hot days) for the days the UCL is exceeded will provide incite into specific assigned variables which need close scrutiny and may require additional controls or replacement. This will allow the site manager to detect and mitigate potential problems before they become significant.

Influence of Subgroup Definition -- The control chart plotted on Figure 3-8 is based on subgroups defined by all tests performed on a given day. Alternate subgroups could include all tests performed on a given compacted soil lifts, seams by crew, etc. Subgroup definition using assigned variables may aid in the detection of trends hidden by larger subgroups. For example, control charts for the data presented on Table 3-7 are developed using subgroups defined by day-of-test and lift number. These control charts are shown on Figure 3-9 and clearly demonstrate how the selection of the subgroup can be used to highlight defective work. When *testing days* defines the subgroups, there are clearly three unacceptable days with several other days approaching the upper control limit. Conversely, the data appears acceptable when *individual lifts* are used to define the subgroups. The subgroups must be defined as small as practical to determine the influence of assignable variables.

(1) Subgroup Number	(2) Subgroup Size	(3) Subgroup Defectives	(4) p= (3)+(2)	(5) sqrt of (2)	(6) c + (5)	(7) LCL= Pbar-(6)	(8) UCL=Pbar+(6)
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
totals							

COLUMN DEFINITIONS

(1) Subgroup Number: Convienent sample grouping, e.g. tests in a given day
(2) Subgroup Size: Number of tests in sample group, e.g. # tests on a given day
(3) Subgroup Failures: Number of tests that fail in subgroup
(4) Ratio of Failures in Subgroup
(5) Square Root of Subgroup Size
(6) C = 3* sqrt (p*(1-p))
(7) Lower Control Limit = Pbar - (6)
(8) Upper Control Limit = Pbar + (6)

* where Pbar = total number fail - total number of tests (26-360=.072)

Figure 3-7 Tabulated Control Chart

TABULATED CONTROL CHART FOR DT SEAM TESTS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
BASED ON TOTAL SAMPLE GROUP					BASED ON "MOVING" SAMPLE GROUP			
					CUMULATIVE			
SUBGROUP ① NUMBER	SUBGROUP SIZE	SUBGROUP FAILURE	$\bar{P}$=(3)÷(2)	UCL ② SUBGROUP	# SAMPLES	# FAILURES	$\bar{P}$=(7)÷(6)	UCL ② "MOVING"
1	12	1	0.083	0.322	12	1	0.082	0.322
2	14	0	0	0	26	1	0.038	0.150
3	9	1	0.111	0.425	35	2	0.057	0.174
4	7	0	0	0	42	2	0.048	0.147
5	13	1	0.077	0.299	55	3	0.054	0.145
6	15	1	0.067	0.261	70	4	0.057	0.140
7	19	3	0.158	0.408	89	7	0.078	0.163
8	13	2	0.154	0.455	102	9	0.088	0.172
9	14	1	0.071	0.277	116	10	0.086	0.164
10	19	0	0	0	125	10	0.080	0.153
11	17	0	0	0	142	10	0.070	0.134
12	16	1	0.063	0.245	158	11	0.070	0.131
13	7	1	0.143	0.541	165	12	0.072	0.132
14	22	2	0.091	0.275	187	14	0.075	0.133
15	18	1	0.056	0.219	205	15	0.073	0.127
16	16	2	0.125	0.373	221	17	0.077	0.131
17	15	0	0	0	236	17	0.072	0.122
18	16	1	0.063	0.245	252	18	0.071	0.119
19	14	0	0	0	266	18	0.068	0.114
20	16	1	0.063	0.245	282	19	0.066	0.112
21	22	2	0.091	0.275	304	21	0.069	0.133
22	18	1	0.056	0.219	322	22	0.068	0.110
23	16	2	0.125	0.373	338	24	0.071	0.113
24	9	0	0	0	347	24	0.065	0.110
25	13	2	0.150	0.450	360	26	0.072	0.113
TOTAL	360	26	PBAR = 0.072 → $\overline{UCL}$ = 0.113					

① NOTE: EACH SUBGROUP REPRESENTS ONE DAYS TESTING
② UCL = $\bar{P}+3\sqrt{\bar{P}(1-\bar{P})/\#SAMPLES}$

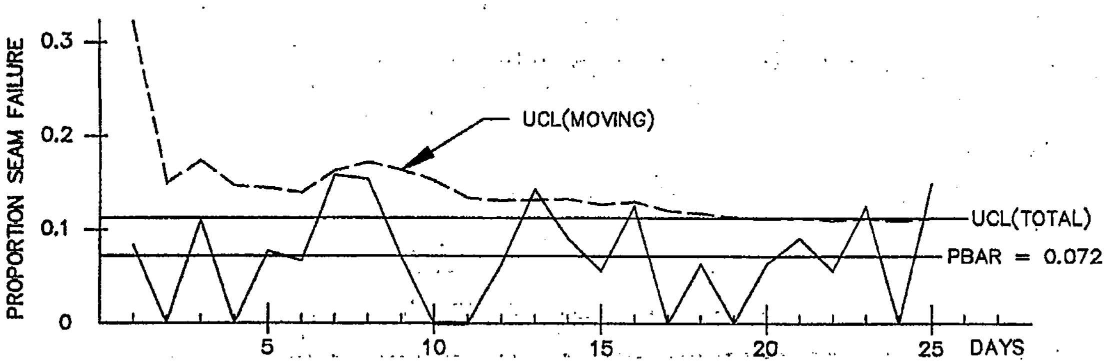
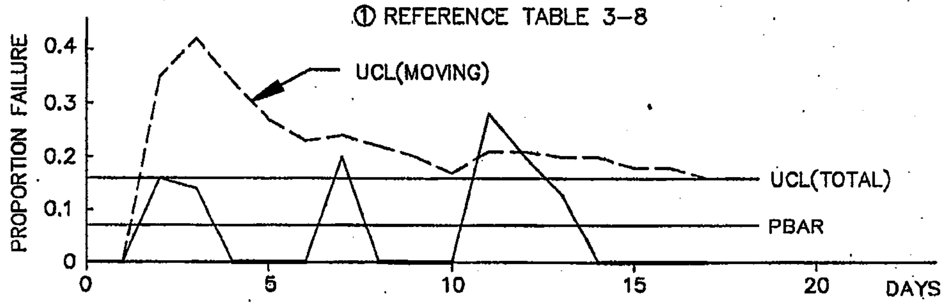


FIGURE 3-8 EXAMPLE - OUTER IDENTIFICATION - FAILURE RATIO

SUBGROUP BASED ON DAYS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
BASED ON TOTAL SAMPLE GROUP					BASED ON "MOVING" SAMPLE GROUP			
					CUMULATIVE			
SUBGROUP NUMBER	SUBGROUP SIZE	SUBGROUP FAILURE	P=(3)÷(2)	UCL ① SUBGROUP	# SAMPLES	# FAILURES	P=(7)÷(6)	UCL ① "MOVING"
1	5	0	0	0	5	0	0	0
2	6	1	0.16	0.60	11	1	0.09	0.35
3	7	2	0.14	0.53	18	3	0.16	0.42
4	5	0	0	0	23	3	0.13	0.34
5	6	0	0	0	29	3	0.10	0.27
6	6	0	0	0	35	3	0.09	0.23
7	5	1	0.20	0.73	40	4	0.10	0.24
8	5	0	0	0	45	4	0.09	0.22
9	5	0	0	0	50	4	0.08	0.20
10	7	0	0	0	57	4	0.07	0.17
11	7	2	0.28	0.79	64	6	0.10	0.21
12	5	1	0.20	0.74	69	7	0.10	0.21
13	8	1	0.13	0.49	77	8	0.10	0.20
14	6	0	0	0	83	8	0.10	0.20
15	6	0	0	0	89	8	0.09	0.18
16	5	0	0	0	94	8	0.09	0.18
17	6	0	0	0	100	8	0.08	0.16
TOTAL	100	7	PBAR = 0.07		$\overline{UCL}$ = 0.16			

① REFERENCE TABLE 3-8



SUBGROUP BASED ON LIFT

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
BASED ON TOTAL SAMPLE GROUP					BASED ON "MOVING" SAMPLE GROUP			
					CUMULATIVE			
SUBGROUP NUMBER	SUBGROUP SIZE	SUBGROUP FAILURE	P=(3)÷(2)	UCL ① SUBGROUP	# SAMPLES	# FAILURES	P=(7)÷(6)	UCL ① "MOVING"
1	20	3	0.15	0.39	20	3	0.15	0.39
2	20	1	0.05	0.19	40	4	0.10	0.24
3	20	2	0.10	0.30	60	6	0.10	0.21
4	20	2	0.10	0.30	80	8	0.10	0.20
5	20	0	0	0	100	8	0.08	0.16
TOTAL	100	8	PBAR = 0.08		$\overline{UCL}$ = 0.16			

① REFERENCE TABLE 3-8

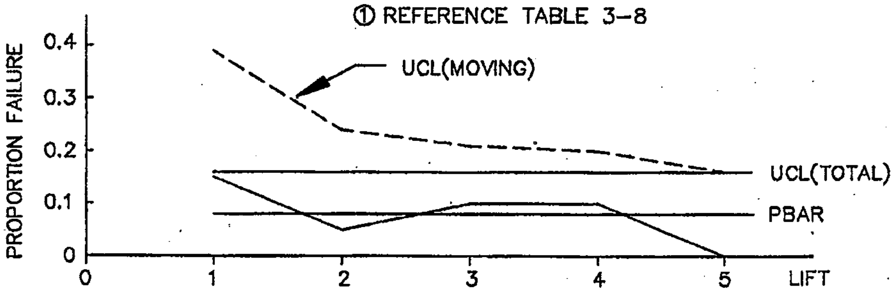


FIGURE 3-9 CONTROL CHART - SUBGROUP SENSITIVITY

3.5 References

3-1 - U.S. EPA. 1984. Permit Applicants' Guidance Manual for Hazardous Waste Land Treatment, Storage, and Disposal Facilities - Final Draft. EPA 530 SW-84-004, Office of Solid Waste and Emergency Response, Washington, DC 20460.

3-2 - U.S. EPA. 1984. Quality Assurance Handbook for Air Pollution Measurement Systems: Volume 1 Principles. EPA-600/9-76-005, Environmental Monitoring Systems Laboratory, Research Triangle Park, NC 27711.

3-3 - Wahls, H.E., et al, The Compaction of Soil and Rock Materials for Highway Purposes, Bureau of Public Roads, Washington, DC, August 1966.

3-4 - Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, PA 19103, 1990.

3-5 - ACI Manual of Concrete Practice, Part 2, Construction Practices and Inspection Pavements, Detroit, Michigan 48219, 1984.

3-6 - Pyzdek, Thomas, (1989), What Every Engineer Should Know About Quality Control, ASQC Quality Press, Milwaukee, Wisconsin.

3-7 - Department of Defense (1964), Sampling Procedures and Tables for Inspection By Attributes, MIL-STD-105, Naual Publications and Forms Center.

3-8 - ASQC (1978), Terms and Symbols for Acceptance Sampling, ANSI/ASQC AZ.

3-9 - U.S EPA 1991. Technical Guidance Document: Inspection Techniques for the Fabrication of Geomembrane Field Seams. EPA/530/SW-91/051, Office of Solid Waste and Emergency Response, Washington, D.C. 20460.

APPENDIX A - WASTE CONTAINMENT ELEMENT FIELD SAMPLE PLANS & TEST METHODS

COMPONENT	ELEMENT	KEY PROPERTY	CQA/CQC TEST	SAMPLING PLAN	SAMPLING FREQUENCY	STANDARD TEST METHOD
Hydraulic Barriers	Geomembrane	Subgrade	Visual	100%		N/A
		Anchor Trench	Visual	100%		N/A
		Sheet Placement	Visual	100%		N/A
		Overlap of Sheets	Measurement	100%		N/A
		Cleanliness of Seam	Visual	100%		N/A
		Extent of Grinding	Measurement	100%		N/A
		Surface Defects	Visual	100%		
			Non Destructive Seam Testing of the S			
			Air Lance	100%		ASTM D4437
			Mechanical Point	100%		N/A
			Electric Spark	100%		N/A
			Pressurized Dual Seam	100%		N/A
			Vacuum Chamber	100%		ASTM D4437
			Ultrasonic Shadow	100%		GRI GM1-86
			Ultrasonic Pulse Echo	100%		ASTM D4437
			Destructive Testing of the Seams			
			Peel Adhesion	Fixed Inc./Judgemental	500 ft	ASTM D413
			Bond Seam Strength			
			Scrim Reinforced	Fixed Inc./Judgemental	500 ft	ASTM D751
			Rubber Geomembrane	Fixed Inc./Judgemental	500 ft	ASTM D816
			All Others	Fixed Inc./Judgemental	500 ft	ASTM D882
				Fixed Inc./Judgemental	500 ft	ASTM D638
	Geomembrane Interlocking Panel	Sheet Placement	Visual	100%		N/A
		Interlock Fit	Visual	100%		N/A
		Trench Depth	Measurement	Fixed Inc./Judgemental		N/A
	Grouts	Viscosity	Viscosity of Grouts	Fixed Inc./Judgemental	1/Batch	ASTM D4016
		Unit Weight	Density of Slurry	Fixed Inc./Judgemental	1/Batch	ASTM D4380
		Slump	Slump Test	Fixed Inc./Judgemental	1/Batch	ASTM C143
		Compressive Strength	Comp Strength Test	Stratified Random	1/Batch	ASTM D4832
		Spacing of Pipes	Measure	100%		N/A
		Depth of Pipe	Measure	100%		N/A
		Quantity Injected	Measure	100%		N/A
		Pressure of Injection	Measure	100%		N/A
	Soil-Bentonite	Proportions of Mix	Measure/Calculate the Weights	Random		N/A
		Uniformity of Mix	Visual	100%		N/A
		Depth of Mixture	Measurement	Random		N/A
		Concentration of Bentonite	Methylene Blue Test	Random	500 cy	N/A
	Bentonite Board	Sheet Placement	Visual	100%		
		Overlap of Sheet	Visual	100%		
		Sheet Defects	Visual	100%		
		Weight Bentonite	Weight	Fixed Increment	1/Lot	
	Bentonite Slurries	Viscosity	Viscosity of Grouts	Fixed Increment	1/Batch	ASTM D4016
		Unit Weight	Density of Slurry	Fixed Increment	1/Batch	ASTM D4380
		Gradation	Sand Content Test	Fixed Increment	1/Batch	ASTM D4381
		Trench Location	Measurement	100%		N/A
		Trench Depth	Measurement	100%		N/A
		Time For Hydration	Measurement	100%		N/A
	Concrete-Bentonite	Viscosity	Viscosity of Grouts	Fixed Increment	250 cy	ASTM D4016
		Unit Weight	Density of Slurry	Fixed Increment	250 cy	ASTM D 4380
		Gradation	Sand Content Test	Fixed Increment	250 cy	ASTM D4381
		Trench Location	Measurement	100%		N/A
		Trench Depth	Measurement	100%		N/A
		Time for Hydration	Measurement	100%		N/A
		Cement Content	Cement Content	Random	250 cy	ASTM D2901

COMPONENT	ELEMENT	KEY PROPERTY	CQA/CQC TEST	SAMPLING PLAN	SAMPLING FREQUENCY	STANDARD TEST METHOD
	Clay Liner	Visual Classification	Visual Identification of soils	Fixed Increment	1500 cy	ASTM D4083
		Clod Size	Measurement	Random		N/A
		Water Content	Water Content-Oven	Random	500 cy	ASTM D2216
		(one only)	Water Content-Micro	Random		ASTM D4643
		Plasticity of Soil	Plasticity Index Test	Random	1500 cy	ASTM D4318
		Gradation of Soil	Gradation Test	Random	1500 cy	ASTM D422
		Organic Content	Organic Content Test	Judgemental		ASTM D2974
		Maximum Density	Proctor Test	Judgemental	5000 cy	ASTM D698 or D1557
		Hydraulic Conductivity	Lab Hydr Cond Test	Random	10,000 cy	
		In-Place Density	Density Test	(Select One)		
			Nuclear	Stratified Random	500 cy	ASTM D2922
			Sleeve	Stratified Random	500 cy	ASTM D4564
			Balloon	Stratified Random	500 cy	ASTM D2167
			Drive-Cylinder	Stratified Random	500 cy	ASTM D2937
		In-Place Hydraulic Conductivity	Infiltrometer	Judgemental	10000 cy	
		Lift Thickness	Measurement	Random		N/A
		Bond Between Lifts	Visual	100%		N/A
		Stripping of Topsoil From Subgrade	Visual	100%		N/A
		Elevations of Finished Grade	Surveying	N/A		N/A
Hydraulic Conveyance	Sand/Gravel Drain/Collector	Water Content	Water Content-Oven	Random		N/A
			Water Content-Micro	Random		N/A
		Gradation of Soil	Gradation Test	Random	1500 cy	N/A
		Hydraulic Conductivity	Lab Hydr Cond Test	Random	5000 cy	N/A
		Lift Thickness	Measurement	Random	3000 cy	N/A
	Geosynthetic Drain/Collector	Overlap of Panels	Measurement	Random		N/A
		Folds or Wrinkles	Visual Observation	100%		N/A
		Temporary Anchorage	Visual Observation	100%		N/A
	Pipe	Placement	Visual Observation	100%		N/A
		Location	Surveying	N/A		N/A
		Grade	Surveying	N/A		N/A
		Continuity of Joints	Pressure Test	100%		
	Sumps	Subgrade	Visual Observation	100%		N/A
		Anchor Trench	Visual Observation	100%		N/A
		Sheet Placement	Visual Observation	100%		N/A
		Overlap of Sheets	Measurement	100%		N/A
		Cleanlines of Seam	Visual Observation	100%		N/A
		Extent of Grinding	Measurement	100%		N/A
			Non Destructive Testing of the Seams			
			Air Lance	100%		ASTM D4437
			Mechanical Point	100%		N/A
			Electric Spark	100%		N/A
			Presized Dual Seam	100%		N/A
			Vacuum Chamber	100%		ASTM D4437
			Ultrasonic Shadow	100%		GRI GM1-86
			Ultrasonic Pulse Echo	100%		ASTM D4437
			Destructive Testing of the Seams			
			Peel Adhesion	Judgemental	1/Seam	ASTM D413
			Bond Seam Strength	Judgemental	1/Seam	
			Scrim Reinforced	Judgemental	1/Seam	ASTM D816B
			Rubber Geomembrane	Judgemental	1/Seam	ASTM D882(mod)
			All Others	Judgemental	1/Seam	ASTM D638
	Pumps	Mounting & Electrical Connection	Visual Observation	100%		N/A

COMPONENT	ELEMENT	KEY PROPERTY	CQQA/CQC TEST	SAMPLING PLAN	SAMPLING FREQUENCY	STADARD TEST METHOD
Filters	Sand/Gravel Filter	Water Content	Water Content-Oven	Random	1500 cy	ASTM D2216
			Water Content-Micro	Random	1500 cy	ASTM D4643
		Gradation of Soil	Gradation Test	Random	1500 cy	ASTM D422
		Hydraulic Conductivity	Lab Hydr Cond Test	Random	3000 cy	
		Lift Thickness	Measurement	Random		N/A
	Geotextile	Overlap of Panels	Measurement	100%		N/A
		Folds or Wrinkles	Visual Observation	100%		N/A
		Temporary Anchorage	Visual Observation	100%		N/A
Erosion Control	Stone & Rip-rap	Size of Stone	Measurement	Random		N/A
			Gradation	Random	10000 cy	ASTM D422
		Lift Thickness	Measurement	Random		N/A
		Presence of Geotextile	Visual Observation	100%		N/A
	Vegetation & Topsoil	Application Rate	Measurement	Fixed Increment		N/A
		Watering Schedule	Measurement	N/A		N/A
		Water Content	Water Content-Oven	Random	3000 cy	ASTM D2216
			Water Content-Micro	Random	3000 cy	ASTM D4643
		Gradation of Soil	Gradation Test	Random		ASTM D422
		Soil pH	Soil pH Test	Random	2 per acre	
		Lift Thickness	Measurement	Random		N/A
		Grade	Surveying	N/A		N/A
		Organic Content	Measurement	Random	1 per acre	ASTM C311
Protective Layer	Hardened Layer					
	Asphalt Layer	Thickness of Asphalt	Measurement	Random		N/A
		Continuity of Joints	Visual Observation	Random		N/A
	Concrete	Temperature of Conc.	Measurement	Fixed Increment		ASTM C143
		Slump	Slump Test	Fixed Increment		ASTM C231
		Entrained Air	Air Content	Fixed Increment		ASTM C31
		Test Cylinders	Making Cylinders	Fixed Increment		ASTM C39
		Compressive Strength	Comp Strength Test	Random		N/A
		Subgrade	Visual Observation	100%		N/A
		Formwork	Visual Observation	100%		N/A
	Biotic Layer	Size of Stone	Measurement	Random		N/A
			Gradation	Random	3000 cy	ASTM D422
		Lift Thickness	Measurement	Random		N/A
		Presence of Geotextile	Visual Observation	100%		N/A
	Geotextile	Overlap of Panels	Measurement	100%		N/A
		Folds or Wrinkles	Visual Observation	100%		N/A
		Temporary Anchorage	Visual Observation	100%		N/A
	Soil Layer	Visual Classification	Visual Identification of Soils	Fixed Increment	3000 cy	ASTM D4083
		Water Content (one only)	Water Content-Oven	Random	5000 cy	ASTM D2216
			Water Content-Micro	Random	5000 cy	ASTM D4643
		Plasticity of Soil	Plasticity Index Test	Random	5000 cy	ASTM D4318
		Gradation of Soil	Gradation Test	Random	5000 cy	ASTM D422
		Maximum Density	Proctor Test	Judgemental	5000 cy	ASTM D698
		Hydraulic Conductivity	Lab Hydr Cond Test(if req'd)	Random	10,000 cy	(std/D1557/mod)
		In-Place Density	Density Test	(select one)		
			Nuclear	Stratified Random	1500 cy	ASTM D2922
			Sleeve	Stratified Random	1500 cy	ASTM D4564
			Balloon	Stratified Random	1500 cy	ASTM D2167
			Drive-Cylinder	Stratified Random	1500 cy	ASTM D2937
		Lift Thickness	Measurement	Random		N/A
		Elevations of Finished Grade	Surveying	N/A		N/A

COMPONENT	ELEMENT	KEY PROPERTY	CQA/CQC TEST	SAMPLING PLAN	SAMPLING FREQUENCY	STANDARD TEST METHOD
Earthwork	Foundation	Proof-Rolling	Visual Observation	100%		N/A
		Visual Classification	Visual Identification			
			of Soils	Fixed Increment	3000 cy	ASTM D4083
		Water Content	Water Content-Oven	Random	1500 cy	ASTM D2216
			Water Content-Micro	Random	1000 cy	ASTM D4643
		Plasticity of Soil	Plasticity Index Test	Random	3000 cy	ASTM D4318
		Gradation of Soil	Gradation of Soil	Random	3000 cy	ASTM D422
		Maximum Density	Proctor Test	Judgemental	10,000 cy	ASTM D698(std)
		Hydraulic Conductivity	Lab Hydr Cond Test	Random		ASTM D1557(mod)
		In-Place Density	Density Test	(select one)		
			Nuclear	Stratified Random	1500 cy	ASTM D2922
			Sand Cone	Stratified Random	1500 cy	ASTM D1556
			Sleeve	Stratified Random	1500 cy	ASTM D4564
			Balloon	Stratified Random	1500 cy	ASTM D2167
			Drive-Cylinder	Stratified Random	1500 cy	ASTM D2937
		Lift Thickness	Measurement	Random		N/A
		Elevations of Finished				
		Grade	Surveying	N/A		N/A
	Soil Embankment	Visual Classification	Visual Identification			
			of Soils	Fixed Increment	3000 cy	ASTM D4083
		Water Content	Water Content-Oven	Random	1500 cy	ASTM D2216
			Water Content-Micro	Random	1000 cy	ASTM D4643
		Plasticity of Soil	Plasticity Index Test	Random	3000 cy	ASTM D4318
		Gradation of Soil	Gradation of Soil	Random	3000 cy	ASTM D422
		Maximum Density	Proctor Test	Judgemental	10,000 cy	ASTM D698(std)
		In-Place Density	Density Test	(select one)		ASTM D1557(mod)
			Nuclear	Stratified Random	1500 cy	ASTM D2922
			Sand Cone	Stratified Random	1500 cy	ASTM D1556
			Sleeve	Stratified Random	1500 cy	ASTM D4564
			Balloon	Stratified Random	1500 cy	ASTM D2167
			Drive-Cylinder	Stratified Random	1500 cy	ASTM D2937
		Lift Thickness	Measurement	Random		N/A
		Elevations of Finished				
		Grade	Surveying	N/A		N/A
	Soil Bedding	Visual Classification	Visual Identification			
			of Soils	Fixed Increment	3000 cy	ASTM D4083
		Water Content	Water Content-Oven	Random	1500 cy	ASTM D2216
			Water Content-Micro	Random	1000 cy	ASTM D4643
		Plasticity of Soil	Plasticity Index Test	Random	3000 cy	ASTM D4318
		Gradation of Soil	Gradation of Soil	Random	3000 cy	ASTM D422
		Maximum Density	Proctor Test	Judgemental	10,000 cy	ASTM D698(std)
		Hydraulic Conductivity	Lab Hydr Cond Test	Random		ASTM D1557(mod)
		In-Place Density	Density Test	(select one)		
			Nuclear	Stratified Random	1500 cy	ASTM D2922
			Sand Cone	Stratified Random	1500 cy	ASTM D1556
			Sleeve	Stratified Random	1500 cy	ASTM D4564
			Balloon	Stratified Random	1500 cy	ASTM D2167
			Drive-Cylinder	Stratified Random	1500 cy	ASTM D2937
		Lift Thickness	Measurement	Random		N/A
		Elevations of Finished				
		Grade	Surveying	N/A		N/A
	Geotextile Separator	Overlap of Panels	Measurement	100%		N/A
		Folds or Wrinkles	Visual Observation	100%		N/A
		Temporary Anchorage	Visual Observation	100%		N/A

APPENDIX B STANDARDIZED TEST METHODS ORGANIZATION ADDRESS

American Society for Testing of Materials (ASTM)
1916 Race Street
Philadelphia, PA 19103

(215) 299-5400

Geosynthetic Research Institute (GRI)
Drexel University
West Wing - Rush Building #10
Philadelphia, PA 19104

(215) 895-2343

Plastics Pipe Institute
355 Lexington Avenue
New York, NY 10017

(212) 351-5420

Asphalt Institute
Asphalt Institute Building
College Park, MD 20740

(301) 656-5824

American Concrete Institute
Box 19150
Detroit, MI 48219

(313) 532-2600

Portland Cement Association
5420 Old Orchard Road
Skokie, IL 60077

(708) 966-6200

National Sanitation Foundation
3475 Plymouth Road
Ann Arbor, MI 48106

(313) 769-8010

APPENDIX C

SAMPLE SPECIFICATIONS FOR A 60 MIL GEOMEMBRANE LINER WITH SAMPLING, TESTING AND ACCEPTANCE CRITERIA

A. Scope of Work

1. The General Contractor shall furnish all labor, material and equipment to install geomembrane including all necessary and incidental items as detailed or required to complete the installation in accordance with the Contract Drawings and these Contract Specifications. The General Contractor shall be responsible for timely submittals to the Engineer as required in this Contract Specifications.

2. The anchor trench shall be excavated, maintained and backfilled by the General Contractor.

B. Material

1. The material for the Geomembrane shall be an approved High Density Polyethylene (HDPE) geomembrane in strict accordance with the Contract Drawings and these Contract Specifications. The geomembrane shall be approved by the Engineer and the County prior to Contract award.

2. The Manufacturer of the geomembrane described herein shall have previously demonstrated his ability to produce the required geomembrane by having successfully manufactured a minimum of ten million square feet of High Density Polyethylene geomembrane for hydraulic containment purposes. The General Contractor shall provide a certification to the above requirements.

3. Material for the geomembrane shall include pure High Density Polyethylene and carbon black, added for ultraviolet radiation resistance, and a maximum of 1 percent of other additives by weight. The geomembrane shall be manufactured of new, first quality products designed, manufactured and furnished by means consistent with National Sanitation Foundation (NSF) Standards. The geomembrane manufacturer shall have demonstrated, by successful prior use, that said material is suitable and dependable for such purposes.

4. The High Density Polyethylene used in the manufacture of the geomembrane shall be of high molecular weight and in accordance with the physical property

requirements of the Contract Specifications. The geomembrane shall be produced so as to be free of holes, blisters, undispersed raw materials or any sign of contamination by foreign matter. Any such defect shall be repaired as approved by the Engineer. The Engineer may reject all or portions of units (or rolls) of geomembrane if significant quantities of production flaws are observed. The physical properties of the geomembrane shall be as described on Table 1 at the end of this Contract Specifications.

5. The geomembrane producer shall submit a certification and supporting test data stating that each resin used for geomembrane production meets or exceeds the environmental stress cracking criteria outlined below.

   5.1 The resin shall exhibit a ductile/brittle transition time of greater than 100 hours using the Notched Constant Load Test (GRI - GM5 Condition A). The transition shall occur at a stress less than 35% of the geomembrane yield stress as determined using ASTM D638.

6. A written certification shall be provided by the geomembrane manufacturer stating the producer, product designation, lot or batch number, and production date of all resin used in manufacture of all HDPE materials shipped to the site.

   6.1 This certification shall be submitted to the Engineer by the Geomembrane Contractor prior to or coincident with shipment of the geomembrane. Geomembrane shall not be accepted or approved unless all required certifications have been received by the Engineer.

7. Thickness of the finished Geomembrane shall be -4% to +10% of the nominal thickness value specified.

8. The outside of each roll shall identify product designation, the thickness of the sheet, panel number, if applicable, the length and width of each roll and manufacturer's batch or lot number.

   8.1 Labels or marking shall be located so that each roll of geomembrane can be identified by examining the roll or core edges. Markings or labels shall be weather proof.

9. No factory seaming of HDPE Geomembrane panels shall be accepted.

10. All compound ingredients (raw material) for HDPE geomembrane shall be randomly sampled and tested by the Geomembrane Manufacturer. A test result summary shall be furnished to the Engineer to assure compliance with the

material requirements of this specification item. The sampling frequency and testing procedures shall comply with the requirements as outlined in Table 1 of these Contract Specifications. A copy of the testing program, including frequency of tests per quantity of raw material and test method procedures, shall be submitted to the Engineer with the General Contractor bid. The summary of test results reflecting actual test frequency shall be furnished to the Engineer prior to or coincident with shipment of the geomembrane to the project site.

11. During production, the HDPE geomembrane manufacturer shall sample and test the manufactured sheet in accordance with applicable ASTM Standards. The minimum sampling frequency, testing procedures, and sheet physical properties, shall comply with the requirements as outlined in Table 1 of these Contract Specifications.

12. The General Contractor shall submit a certification stating the percent of reclaimed polymer, by weight, that was incorporated into production of the lots or batches of geomembrane delivered to the project site. Reclaimed polymer shall not exceed 2% by weight for geomembrane or extrudate.

12.1 At the option of the County, the Engineer may inspect the geomembrane manufacturing process on a full-time basis. The inspection program includes conformance sampling as required. The geomembrane manufacturer shall submit a production schedule to the County if requested and cooperate with the County during plant inspection.

13. The General Contractor shall submit a certification to the Engineer, prior to installation, that all HDPE geomembrane manufactured for the project has been produced in accordance with these specifications, and that a Quality Control testing program, in accordance with the Contract Specifications and approved by the Engineer, has been in effect, and that all required tests have been performed.

14. The certified summary of all raw material and sheet material tests including testing frequency and test methods used shall be issued to the Engineer prior to geomembrane delivery. No HDPE geomembrane shall be installed until the Engineer has reviewed the certified test summary and determined the geomembrane delivered is acceptable for use. Records, including test data, shall be maintained by the geomembrane manufacturer for one year and shall be made available upon request.

15. The General Contractor shall submit Quality Control Certificates reviewed and signed by the responsible representative of the geomembrane manufacturer. A Quality Control Certificate shall be submitted to the Engineer for each roll of geomembrane delivered to the project site prior to installation. Any roll not represented by a completed Quality Control Certificate shall not be approved for installation by the Engineer.

16. Quality assurance conformance testing of the geomembrane shall be performed by the Engineer and paid for by the County. Conformance sampling shall be completed at a minimum frequency of one sample every 100,000 square feet of geomembrane delivered and at least one sample per lot or batch as directed by the Engineer.

    16.1 Conformance testing of the geomembrane shall include but not be limited to the following properties:

        16.1.1 Density, ASTM D792
        16.1.2 Melt Flow Index, ASTM D1238
        16.1.3 Thickness, ASTM D1593
        16.1.4 Tensile Properties, ASTM D638
        16.1.5 Tear Resistance, ASTM D1004
        16.1.6 Carbon Black Content, ASTM D1603
        16.1.7 Carbon Black Dispersion, ASTM D3015

    16.2 The Engineer may revise the test methods used for determination of conformance properties to allow for use of improved methods.

17. All geomembrane conformance test data as well as geomembrane manufacturer Quality Control testing shall meet or exceed requirements outlined in Table 1 of these Contract Specifications prior to installation. Any materials that do not conform to these requirements shall be retested or rejected at the direction of the Engineer.

    17.1 Geomembrane that is rejected shall be removed from the project site and replaced at General Contractor's cost. Sampling and conformance testing of geomembrane supplied as replacement for rejected material shall be performed by the Engineer at the General Contractor's cost.

C. **Installation - Geomembrane Preparation and Placement**

1. The Geomembrane Contractor must be approved by the Engineer and the County prior to Contract award. General Contractor qualifications shall be submitted for approval with the Geomembrane Contractor's bid, certifying he has installed a minimum of five million square feet of HDPE geomembrane for hydraulic containment purposes.

   1.1 The General Contractor shall be responsible for timely submittals to the Engineer and the County.

2. Approximately two weeks prior to arrival at the job site, the Geomembrane Contractor shall provide personnel resumes demonstrating compliance with the following requirements:

   2.1 A minimum of one field superintendent per shift shall be designated by the Geomembrane Contractor and approved by the Engineer and the County. Each field superintendent shall have a minimum of one year of field experience in installing HDPE geomembranes. Any change or replacement of superintendents during the project must be approved in advance by the Engineer and the County.

   2.2 Each seaming crew shall have a designated foreman. Said foreman must have a minimum one year HDPE geomembrane installation experience and must work continuously with the seaming crew.

3. The Geomembrane Contractor shall submit for the Engineer's approval, approximately two weeks prior to geomembrane shipment, six full sets of field erection drawings showing geomembrane panel layout with proposed length and width, number and position of all geomembrane panels and indicating the location of all field welds. Field welds shall have a distinct identification system. Erection drawings shall also show complete details for field seaming and repairs, anchoring the geomembrane at the perimeter of the installation area, joining to structures, and attachments to other penetrations as required.

4. Prior to scheduled geomembrane installation, the General Contractor, Engineer and General Contractor shall be required to attend a pre-construction meeting at the project site. This meeting shall be scheduled by the County after receipt of field erection drawings.

   4.1 The General Contractor shall be represented by both the project field superintendent and the project manager.

4.2 At the pre-construction meeting, site safety and rules of operation, quality assurance, scheduling and methods of installation shall be discussed. The General Contractor and Engineer shall at this time agree to the required welding, testing and repair procedures.

5. A daily field record shall be maintained by the General Contractor of actual placement of each panel, noting the condition of subgrade, weather, seaming parameters, panel numbers placed, seams welded, samples taken and tests run. A copy of each day's field record shall be submitted to the Engineer or his representative no later than the following work day.

6. The surfaces that are to receive the geomembrane shall be prepared in accordance with the Contract Drawings and Contract Specifications. Once the subgrade has been approved by the Engineer, any additional surface preparation that the General Contractor feels necessary to meet the requirements of the Contract Specifications, shall be the responsibility of the General Contractor. The General Contractor shall install geomembrane only on approved subgrade that has been approved in writing by the General Contractor and the Engineer.

6.1 The geomembrane shall be placed only on subgrade that is free from rutting or other evidence of damage caused by vehicle traffic, erosion or other causes. Subgrade surface requirements, including allowances for desiccation cracking shall be as outlined in other applicable section of these Contract Specifications.

6.2 Areas exhibiting deficient subgrade surface shall be reported to the Engineer and the County for repair.

7. It is imperative to keep surface water runoff from beneath the geomembrane at all tim es during installation. The General Contractor's panel placement, seam welding technique, placement and welding schedule shall minimize or eliminate the potential for accumulation of water beneath the geomembrane. Any water found ponded beneath the geomembrane after the geomembrane has been installed shall be removed by the General Contractor at no cost to the County as directed by the Engineer. Any soil subgrade beneath installed geomembrane that has become excessively moist, soft, or unsuitable to perform its intended function shall be removed and replaced by the General Contractor, as directed by the Engineer, at the General Contractor's expense.

8. Under no circumstances shall any construction or vehicular traffic be allowed to drive over the exposed geomembrane. Geomembrane showing evidence of traffic shall be inspected by the General Contractor and Engineer to determine

damage, if any. At the direction of the Engineer, any such material shall be tested, rejected or repaired at no cost to the County.

9. Extreme care shall be taken by personnel while handling unwrapping, transporting, positioning, and seaming the geomembrane. The Engineer shall have the option of inspecting all geomembrane panels, prior to final placement, to assure that all defects or damages are identified for repair. This shall not replace final inspection by the General Contractor after installation is complete. Damage to geomembrane incurred during delivery, storage, or installation shall be repaired or replaced at General Contractor expense.

   9.1 Geomembrane shall be stored in a suitable area designated by the County. Geomembrane delivered on pallets or with folds or creases of any kind shall be rejected and removed from the site.

   9.2 Geomembrane shall be protected during storage so that roll labels remain in-tact and readable. Any roll of geomembrane that has no label or where the label is damaged or otherwise illegible may be rejected by the Engineer.

10. The General Contractor shall provide temporary anchorage of the geomembrane during installation in a manner approved by the Engineer. Any geomembrane exhibiting damage from wind or other causes shall be removed by the General Contractor at no cost to the County.

11. The General Contractor shall be responsible for excavation and maintenance of the geomembrane anchor trench as well as backfilling of the anchor trench.

   11.1 The anchor trench shall be "daylighted" to allow drainage while the trench is open. The General Contractor shall be responsible for preventing surface water runoff from accumulating beneath or over top of geomembrane while the anchor trench is open.

12. The geomembrane shall be installed so as to eliminate "trampolining" of the geomembrane at the toe of slopes at temperatures as low as 0°F. If trampolining is observed, the Engineer shall direct required repair in affected areas to be performed by the General Contractor at General Contractor's expense.

13. Extrusion or fusion welds of adjacent panels shall extend continuously along the full length of panels and into the geomembrane anchor trench.

14. The General Contractor shall place the geomembrane in such a manner that no seams exist in any sump bottom, or, as applicable, within 5 ft. laterally of sidewall riser pipe locations.

15. The General Contractor shall place and seam geomembrane panels in order to assure adequate, well distributed slack exists to account for expansion or contraction of the geomembrane. For this purpose, the General Contractor may use a working range of <u>liner</u> temperatures from 0 to 150°F to determine the required techniques.

    15.1 In critical areas such as sidewalls, sumps, and corners, the General Contractor may propose slack control techniques for approval by the Engineer.

16. Seams shall be oriented in a direction parallel to the line of maximum subgrade slope and shall be placed in a manner that minimizes the number and length of field seams.

17. For geomembranes placed on slopes, the panels shall be placed such that the "upstream" panel forms the upper panel and overlaps the "downstream" panel in order to minimize infiltration potential.

18. All longitudinal seams shall be at least 10 ft. from the toe of the sideslope, except in the sump area as directed by the Engineer.

D. <u>Installation - Production Seaming of Geomembrane</u>

1. All seaming, sealing and welding material shall be of a type or types recommended by the Geomembrane Manufacturer and shall be delivered in the original sealed containers, each with an indelible label bearing the brand name, manufacturer's batch or lot number, and complete directions as to proper storage.

2. No production seaming shall commence until trial seaming, as outlined in section of these Contract Specifications, is successfully completed and approved by the Engineer.

3. The Engineer and the County, in conjunction with the General Contractor, shall establish site-specific limits of weather conditions -including, but not limited to, temperature, humidity, precipitation and wind speed and direction - within

which geomembrane panel placement and seaming can be conducted. In the absence of site-specific criteria, the following limitations shall apply:

3.1 No seaming shall be conducted in the presence of precipitation, such as rain, snow, sleet, dew or fog, in or below the seam area.

3.2 No seaming shall be conducted in the presence of high winds, when dirt or debris is blown into seam areas, or when seam temperatures cannot be adequately monitored and controlled.

3.3 Seaming shall not be conducted when ambient temperature falls below 35°F unless approved by the Engineer. In order for seaming to be approved, the General Contractor shall be required, at a minimum, to perform an additional trial seam to demonstrate conformance with these Contract Specifications. The Engineer reserves the right to require additional destructive seam testing when seaming is conducted at ambient temperatures below 35°F.

3.3.1 The General Contractor shall be prepared to pre-heat the seam area prior to production seaming in accordance with the Geomembrane Manufacturer recommendations.

3.4 Seaming shall not be conducted when ambient temperature exceeds 104°F unless approved by the Engineer. Criteria for demonstration of conformance shall be outlined by the Engineer.

4. For purposes of monitoring production geomembrane seaming, ambient temperature shall be monitored by the Engineer. Ambient temperature shall be recorded at multiple locations along the seam at a distance of 6-inches above the geomembrane surface.

5. Lap joints shall be used to weld panels of HDPE geomembrane together in the field. A minimum overlap of 3-inches shall be used. Seams shall be fusion or extrusion-welded and as prescribed by the Geomembrane Manufacturer and approved by the Engineer. For production seaming of geomembrane panels, fusion seaming is the preferred method. Panels shall be held in position in a manner approved by the Engineer, to prevent movement during welding, and to maintain a "flat" lap of panels. The weld area shall be prepared to provide a suitable surface for adherence to panels to be welded. The weld area shall be free of dirt, dust, moisture, or other foreign material, and the cleaning process shall be approved by the Engineer. The weld shall be applied as soon as is practical after preparation and cleaning is completed. No glue or tape shall be used to temporarily hold panels together before welding. No solvents shall be used to clean panels prior to welding.

6. Temporary bonding of geomembrane panels or patches to be extrusion welded may be completed using hot air equipment, such as a "Leister". Overheating of the geomembrane during temporary bonding shall result in rejection of the seam or patch in question and repair as directed by the Engineer.

7. All Geomembrane panels placed shall be seamed on the same day that they are placed except where explicitly approved by the Engineer.

8. No folds, wrinkles, or "fish-mouths" shall be allowed within the seam area. Where wrinkles or folds occur, the material shall be cut, overlapped, and a patch shall be applied. During wrinkle or fold repairs, adjacent geomembrane may not necessarily be required to meet the 3-inch minimum overlap, if approved by the Engineer.

9. Engineer shall observe areas to be prepared by grinding, where applicable, to assure that excessive grinding does not occur and that the upper sheet is properly beveled, where applicable.

    9.1 Grinding shall be considered to be excessive when the sheet is deeply scored or when abrasion is evident more than 1/4-inch outside the completed extrusion weld area. The Engineer may require repair of such areas, which may include removal and replacement of the affected geomembrane.

10. The General Contractor shall not cause excessive overheating of the geomembrane. Excessive overheating shall be defined as any of the following:

    10.1 Application of seaming temperatures or seaming rates that result in visible warping or deformation of the bottom surface of the lower geomembrane in the seam area.

    10.2 Seaming over an existing weld ("piggybacking"), except for seam cross tee patches over fusion seams,

    10.3 Seaming using temperatures in excess of the manufacturer's recommended seaming temperature as defined at the pre-construction meeting.

11. Application of a bead of extrudate over damaged geomembrane (bead repairs) shall be prohibited, except where explicitly approved by the Engineer in advance.

  11.1 Surface defects, small tears, punctures, etc. shall be repaired using a patch with a minimum size of 12 inches by 12 inches and having rounded edges.

12. Fusion seams shall not be repaired by placing extrusion welds directly over previously seamed areas. Seam end tabs for fusion seams shall not be removed by cutting or tearing.

  12.1 Under no circumstances shall seams be placed over existing seams for repair purposes unless the affected area is less than 5 ft. in length <u>and</u> is approved by the Engineer in advance.

  12.2 Fusion seams shall be repaired by using a patch or cap strip approved by the Engineer.

13. The Engineer may require repair or replacement of any area where excessive grinding, overheating, or unacceptable preparation, seaming or testing techniques are observed. Such repair or replacement may be required even if samples removed from affected ares pass destructive peel or shear testing.

  13.1 All required repairs shall be completed by the General Contractor at no expense to the County.

14. Any geomembrane area showing damage due to excessive scuffing, puncture or distress from any cause, shall, as directed by the Engineer, be replaced or repaired.

15. All patches for repair of the geomembrane shall have rounded corners such that the repair may be completed with a continuous extrusion weld.

16. Each extrusion welding machine shall be purged of old extrudate prior to the start of each weld run. The extruders used shall be capable of continuously monitoring and controlling the temperatures of the extrudate and the zone of contact (nozzle), to assure compliance with these Contract Specifications and General Contractor field welding recommendations.

E. **Geomembrane Seaming - Test Welds and Test Weld Sampling**

1. The General Contractor shall be responsible for performing field testing of all test welds. The General Contractor shall submit for Engineer's review and approval at the time of bid submittal, a test weld quality control testing program. The General Contractor shall modify the quality control testing program to comply with the Engineer's requirements for testing, sampling and resampling of test welds.

2. Test welds shall be performed for each welder whenever any of the following conditions occur: (1) shift start-up, (2) "cold" restart of the welder, (3) change in welding technician, (4) significant change in ambient temperatures, or (5) as required by the Engineer.

3. Test welds shall at least 5-ft in length and be conducted using the same personnel, equipment and seaming parameters as will be used during production seaming.

4. Sampling of the test weld shall be conducted from the center two-thirds of the seam length once an appropriate cooling period has passed.

5. The General Contractor shall obtain duplicate "preweld" test samples, suitable for testing. One sample shall be kept by the General Contractor for testing at the project site in the presence of the Engineer. The duplicate sample shall be furnished to the Engineer for the project record and/or possible future testing. The duplicate sample shall be marked with date, time, ambient temperature, welder, weather conditions, and welding parameters (heat, rate of travel, etc.). Specimens tested by the General Contractor shall be marked and stored on the project site for inspection by the County or the Engineer.

6. Test results acceptable to the Engineer shall be obtained prior to performing any installation production welding. This may require resampling completed test seams or repeating the trial seam process. The results of tests shall be noted in the General Contractor's "preweld" test summary log or daily diary and a copy furnished to the Engineer not later than the next work day.

7. The trial seam test specimens shall be tested in peel in accordance with the approved quality control testing program. A minimum of three specimens shall be tested for each trial seam. Qualification criteria for all destructive prewelding testing shall be the Film Tear Bond (FTB) criteria. The failure of the seam specimen shall be in the parent sheet, not the weld. Under certain conditions, a partial disbond observed during peel testing of 20% of the weld width or less,

may be accepted by the Engineer. Testing of additional specimens shall be performed as required by the Engineer. A failure within the weld area as designated by the Engineer shall constitute disqualification and require a new trial seam test of the welding equipment, as directed by the Engineer.

7.1 For double hot wedge type seams, both seams shall be tested for all field and laboratory destructive testing.

F. Geomembrane Seaming - Production Seam Testing

1. The General Contractor shall be responsible for completing nondestructive testing of the entire length (100%) of all field seams, including cap strips, and verifying that all seams are watertight. The testing method shall be a vacuum test, air-pressure test, or approved equal. The test procedure shall be described in writing by the General Contractor and submitted with the bid and approved by the Engineer prior to installation. Upon completion of the vacuum testing, air-pressure test, or approved equal, a written report shall be submitted to the Engineer by the General Contractor certifying that all seams were tested.

1.1 Seams or portions of seams that cannot be nondestructively tested due to access constraints or other reasons may be required to be covered with a cap-strip as required by the Engineer.

2. The Engineer shall approve procedures proposed by the General Contractor for nondestructive testing of geomembrane seams including, but not limited to, the following items:

2.1 Vacuum Test (as required)

2.1.1 Test device
2.1.2 Vacuum pressure
2.1.3 Vacuum duration at each location

2.2 Air Pressure Testing (as required)

2.2.1 Maximum pressure
2.2.2 Test duration
2.2.3 Maximum allowable pressure drop
2.2.4 Allowance for geomembrane expansion or contraction during pressure testing
2.2.5 Retesting procedures

3. Where practical, the General Contractor or Engineer shall sample the ends of production seams at the panel ends. Field destructive testing for these samples shall be performed on-site by the General Contractor using the test method and approval criteria outlined in Paragraph E.7 for test weld samples.

   3.1 If the end samples do not exhibit acceptable failures, the Engineer may require that the General Contractor sample additional locations on the same seam and/or adjacent seams for laboratory destructive testing.

4. The General Contractor shall obtain duplicate samples of production welds suitable for destructive testing. The samples shall be obtained at a rate of one pair (sample and duplicate) per 500 linear feet of welded seam. Additional samples shall be removed by the General Contractor from areas of questionable integrity, as directed by the Engineer. The Engineer shall be responsible for destructive testing one of the sample pairs as described in Paragraph F.5. The duplicate sample shall be furnished to the Engineer for the project record and/or possible future testing. These samples shall be obtained from locations as directed by the Engineer and shall be repaired by the addition of a patch to the sampling location. Each sample size shall not be less than 12 inches by 24 inches with the longer dimension measured parallel to the seam. The seam shall be in the center of the sample parallel to the longer dimension of the sample. The seam repair at destructive test sample location shall be nondestructively tested by the General Contractor to verify its integrity.

   4.1 An additional duplicate sample may be retained for testing by the General Contractor. This testing, if performed, shall be completed at no cost to the County.

5. The weld in the destructive sample shall be laboratory tested in peel (ASTM D413) and shear (ASTM D3083). Qualification criteria for all destructive seam testing shall be the Film Tear Bond (FTB) as well as load criteria outlined below. The failure of the seam specimen shall be in the parent sheet, not the weld. Under certain conditions, a partial disbond observed during peel testing of 10% of the weld width or less, may be accepted by the Engineer. A failure within the weld area as designated by the Engineer shall require resampling and retesting, as directed by the Engineer.

   5.1 Five specimens from each laboratory destructive test sample shall be tested for Bonded Seam Strength using ASTM D3083 as modified in NSF Standard Number 54 using 1-inch wide by 6-inch long die cut specimens and a strain rate of 2-inches per minute. The load at failure shall be at least 90 percent of the yield strength (in pounds per inch width) of the parent geomembrane. Failures exhibited in areas prepared by grinding outside of the extruded areas of extrusion seams may require resampling and retesting.

5.2 At least five specimens from each laboratory destructive test sample shall be tested for Peel Adhesion using ASTM D413 as modified in NSF Standard Number 54 using a minimum of 1-inch wide by 6-inch long die cut specimens and a strain rate of 2-inches per minute. The load at failure shall be 60 percent of the yield strength of the parent geomembrane (in pounds per inch width) or greater. Strain at failure shall be at least 30 percent.

5.3 In order for the destructive sample to be considered qualified at least four of the five peel <u>and</u> four of the five shear specimens shall meet all load, strain and FTB criteria. If any specimens fail, the Engineer may test additional specimens in order to determine seam conformance. The Engineer shall determine conformance of each sample in cases of dispute.

6. Destructive laboratory conformance testing shall be the responsibility of the Engineer, and associated costs shall be performed at County expense. The General Contractor shall be responsible for all sampling and repair of sample locations for laboratory and field destructive testing.

7. Should the test results of any destructive test samples removed from production welds not meet the conformance criteria outlined in these Contract Specifications, the Engineer may require that additional samples be taken from welds performed during the same work shift as the failing weld sample. If a destructive sample fails to meet the physical properties required by the Contract Specifications, the General Contractor shall obtain additional test samples a distance of approximately 10-feet in both directions from the original sample for laboratory destructive testing. All resampling, repairing, and retesting shall be the responsibility of the General Contractor and shall be performed at the General Contractor's expense. Depending on the results of these retests, the Engineer shall approve the repair procedure.

7.1 In order to be considered qualified, each failed destructive seam sample shall be bounded by two passing destructive seam samples. Alternatively, the entire length of the seam in question may be repaired by placement of a cap strip.

8. The Engineer or the County may require additional random samples be taken for destructive testing in areas that visually appear defective and/or not in accordance with these Contract Specifications. Testing of these samples shall be completed by the Engineer, but obtaining the samples and repairing the sample areas shall be the responsibility of the General Contractor.

9. A final visual examination of all welds and in-place geomembrane shall be completed by the Engineer. The General Contractor shall repair,in accordance with these Contract Specifications, any area designated by the Engineer as not in accordance with the Contract Specifications. The General Contractor shall be responsible for cleaning, sweeping, or other measures necessary to provide a thoroughly visible geomembrane surface for the Engineer's inspection. The Engineer's inspection shall be performed following a complete inspection and approval by the General Contractor's foreman or designated quality control technician.

G. <u>Warranty</u>

1. The General Contractor shall guarantee the integrity within the realm of the limitations of the General Contractor's responsibility of the installed geomembrane for its intended use, from material or installation defects, for a period of two years from the date of acceptance.

2. Such written warranty shall provide for the total and complete repair and/or replacement of any defect or defective areas of geomembrane upon written notification and demonstration by the County of the specific nonconformance of the geomembrane or installation with the Contract Specifications. Such defects or nonconformance shall be repaired and/or replaced expeditiously, at no cost to the County.

3. The General Contractor shall be responsible for obtaining any necessary guarantees or certifications from the Geomembrane Manufacturer and submitting them to the Engineer and Company prior to acceptance of the installed geomembrane.

H. <u>Measurement and Payment</u>

1. Payment for work covered shall be on the basis of the Unit Price Bid for Geomembrane, per square foot in-place including material and installation.

2. Installed quantities shall be determined by the Engineer. Said areas shall be the actual area of lined surface, including the required rubsheets, cap sheets, and geomembrane placed in the anchor trench. This quantity shall not include overlap at seams, cap strip repairs or other repair areas.

3. Payment for geomembrane material shall be made following appropriate storage on site and following approval of all required certification submittals in accordance with these Contract Documents.

4. Delivery date of the geomembrane to the jobsite shall be approved by the County prior to shipment. The General Contractor shall be responsible for unloading and stockpiling materials at time of delivery and in areas approved by the Engineer and the County.

5. Payment for geomembrane installation shall be based upon approved installation quantities through regular progress payments and in accordance with these Contract Specifications.

6. Final payment for geomembrane material and installation shall be withheld by the County until all required documents have been submitted to the Engineer by the General Contractor.

TABLE 1

REQUIRED PHYSICAL PROPERTIES OF 60 MIL HDPE GEOMEMBRANE[1]

PROPERTY (UNITS)	TESTING FREQUENCY	TEST METHOD[2]	MIN/MAX VALUES
Thickness (mils)	each roll	ASTM D751	57-66
Density, (g/cc)	each roll	ASTM D792, Method A-1	0.935 min
Melt Index (g/10 min)	one per lot or batch (railcar)	ASTM D1238, condition 190/2.16	1.0 max
Carbon Black Content (%)	each roll	ASTM D1603	2.00 - 3.00
Carbon Black Dispersion (Grade)	each roll	ASTM D3015	A1 (3)
Minimum Tensile Properties, each direction	each roll	ASTM D638, type IV, specimen @ 2 ipm	
1. Tensile Stress @ Yield (lb/in.)	test in each principal sheet direction		120 min
2. Tensile Stress @ Break (lb/in.)			180 min
3. Elongation @ Yield (%)			10 min
4. Elongation @ Break (%)			600 min
Tear Resistance (pounds)	each roll	ASTM D1004, die C	40 min
Brittleness Temperature (deg F)	one per lot	ASTM D746, Procedure B	-40° F no failures
Notched Constant Load Test	one per resin	GRI GM 5	Transition time >100 hours at < 35% of yield stress
Environmental Stress Crack	one per lot	ASTM D1693, Condition C	0 failures @ 1000 hours

NOTE (1): The required physical properties specified herein may be revised by the Engineer to reflect new or revised test methods or to conform with improvements on the current state-of-the practice.

NOTE (2): Number of specimens per test established in applicable test method unless otherwise noted.

NOTE (3): Grading Observation Standard to be agreed upon between manufacturer and Engineer.

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